FINAL

Remedial Action Plan for the Risk-Based Remediation of Area D

Ellsworth Air Force Base
South Dakota

Prepared For

Air Force Center for Environmental Excellence
Technology Transfer Division
Brooks Air Force Base
San Antonio, Texas

and

Ellsworth Air Force Base
South Dakota

May 1996

Walton, Norman

From: Hansen, Jerry E, Mr, HQAFCEE [Jerry.Hansen@HQAFCEE.brooks.af.mil]
Sent: Tuesday, August 08, 2000 10:16 AM
To: 'nwalton@dtic.mil'
Subject: Distribution statement for AFCEE/ERT reports

Norman, This is a followup to our phone call. The eight boxes of reports you received from us are all for unlimited distribution. If you have any questions, you can contact me at DSN 240-4353.

FINAL

REMEDIAL ACTION PLAN FOR THE RISK-BASED REMEDIATION OF AREA D

ELLSWORTH AIR FORCE BASE
SOUTH DAKOTA

Prepared for

Air Force Center for Environmental Excellence
Brooks Air Force Base
San Antonio, Texas
and
Ellsworth Air Force Base
Sotuh Dakota

May 1996

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List of Acronyms and Abbreviations

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
ARSD	Administrative Rules of South Dakota
AST	Aboveground storage tank
bgs	Below ground surface
BH	Borehole
BTEX	Benzene, toluene, ethylbenzene, xylenes
cm/sec	Centimeters per second
COC	Chemicals of concern
COPC	Chemicals of potential concern
CSM	Conceptual site model
DO	Dissolved oxygen
EPA	Environmental Protection Agency
ES	Engineering-Science, Inc.
ft/day	Feet per day
ft/ft	Foot per foot
f_{oc}	Fractional organic carbon content
gpm	Gallons per minute
HEAST	Health Effects Assessment Summary Tables
HHSM	Hydrocarbon Spill Screening Model
HSA	Hollow-stem auger
IRIS	Integrated Risk Information System
K_D	Distribution partition coefficient
kg	Kilogram

LNAPL	Light nonaqueous-phase liquid
LTM	Long-term monitoring
LTMP	Long-term monitoring plan
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
MDL	Method detection limit
µg/kg	Microgram per kilogram
µg/L	Microgram per liter
µg/m^2-min	Microgram per square meter per minute
mg	Milligram
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
mg/m^3	Milligrams per cubic meter
mm Hg	Millimeter of mercury
MP	Monitoring point
MPA	Monitoring point A
MPB	Monitoring point B
MPC	Monitoring point C
mph	Miles per hour
msl	Mean sea level
MW	Monitoring well
NCP	National Contingency Plan
NMRL	National Risk Management Research Laboratory
NOAA	National Oceanographic and Atmospheric Administration
O&M	Operations and maintenance
OSHA	Occupational Safety and Health Administration

OSWER	Office of Solid Waste and Emergency Response
PAH	Polycyclic aromatic hydrocarbon
Parsons ES	Parsons Engineering Science, Inc.
PEL	Permissible exposure limit
POA	Point-of-action
POL	Petroleum, oil, and lubricant
ppmv	Parts per million per volume
PQL	Practical quantitation limit
psi	Pounds per square foot
PVC	Polyvinyl chloride
QA	Quality assurance
QAPP	Quality assurance project plan
QC	Quality control
RAP	Remedial action plan
RCRA	Resource Conservation and Recovery Act
SAP	Sampling and analysis plan
scfm	Standard cubic feet per minute
SDDENR	South Dakota Department of Environment and Natural Resources
SDWA	Safe Drinking Water Act
SESOIL	Seasonal Soil Compartment Model
THE	Total extractable hydrocarbons
TOC	Total organic carbon
TPH	Total petroleum hydrocarbons
TVH	Total volatile hydrocarbons
TWA	Time-weighted-average
U	Undetected

USACE	US Army Corps of Engineers
USGS	US Geological Survey
UST	Underground storage tank
VOCs	Volatile organic compounds
VW	Vent well

SECTION 1

INTRODUCTION

1.1 PURPOSE AND SCOPE

Parsons Engineering Science, Inc. (Parsons ES), formerly Engineering-Science, Inc. (ES), was retained by the United States (US) Air Force Center for Environmental Excellence (AFCEE) to prepare a remedial action plan (RAP) in support of a risk-based remediation decision for soil and groundwater contaminated with jet fuel hydrocarbons at Area D at Ellsworth Air Force Base (AFB), Rapid City, South Dakota (the Base). Risk-based remediation is designed to combine natural physical, chemical, and biological processes with low-cost source removal technologies such as *in situ* bioventing, as necessary, to economically reduce potential risks posed by subsurface petroleum fuel spills. This RAP is prepared as part of a multi-site initiative sponsored by AFCEE to develop a protocol on how quantitative fate and transport calculations and risk information based on site-specific data can be integrated to quickly determine the type and magnitude of remedial action required at fuel-contaminated sites to minimize contaminant migration and potential receptor risks. Area D is one of eight sites nationwide that will be used as a case study in the development of the protocol. This protocol document is being developed for AFCEE by Parsons ES in cooperation with the Bioremediation Research Team at the US Environmental Protection Agency's (EPA's) National Risk Management Research Laboratory (NMRL), Subsurface Protection and Remediation Division (formerly known as the Robert S. Kerr Environmental Research Laboratory) in Ada, Oklahoma.

This RAP has been prepared to meet the procedural and documentation requirements of both a remedial assessment report and a RAP, as described in Section V, Parts I and II, of the South Dakota Department of Environment and Natural Resources (SDDENR) (1994) *Handbook for Investigation and Corrective Action Requirements for Discharges from Storage Tanks, Piping Systems, and Other Spills* (hereafter referred to as the handbook). The RAP develops and describes a recommended remedial action to be implemented at Area D that would protect human health and the environment from potentially unacceptable risks due to exposure to site-related contamination in soil and groundwater. Concentrations of individual volatile contaminants (Chapter 74:03:32 of the Administrative Rules for South Dakota) were detected in subsurface soil samples collected from areas immediately underlying and adjacent to the Area D underground storage tanks (USTs). Although dissolved concentrations of volatile and polynuclear aromatic hydrocarbon (PAH) contaminants in groundwater also exceed promulgated standards (Chapter 74:03:15), the analysis presented in this RAP shows that concentrations of these contaminants in groundwater are not expected to increase over time, and that minimal downgradient contaminant migration is expected.

Several remedial approaches which rely on both natural contaminant attenuation processes and engineered solutions were evaluated for the site. The remedy proposed in this RAP would ensure that no hazardous substances would migrate at concentrations that may pose a risk to human health and the environment beyond the area that can be placed under reliable exposure controls [i.e., beyond the proposed point of action (POA)]. A site-specific exposure pathways analysis was completed for Area D as part of this effort to ensure that existing and predicted future concentrations of hazardous substances would not pose a threat to current and foreseeable future onsite and offsite receptors. The site-specific analysis demonstrates that no exposure pathway would be complete for onsite workers given current and future land and groundwater uses, and that site-related contamination will not migrate beyond the proposed POA at concentrations in excess of promulgated groundwater quality standards.

In accordance with Appendix 10 of the handbook (SDDENR, 1994), the recommended remedy provides for the removal of hazardous substances from the soil and groundwater through the combined use of low-cost engineered source reduction activities and natural physical, chemical, and biological processes that are documented to be occurring at the site. The analysis included in this RAP demonstrates that supplementing these natural processes with engineered remedial activities will enhance and expedite site cleanup. This RAP is being submitted for review and approval consistent with Section V of the handbook (SDDENR, 1994).

The activities conducted pursuant to the preparation of this RAP included focused site investigation activities and data analysis to characterize:

- The nature and extent of fuel hydrocarbon contamination at the site;
- The local geology, hydrogeology, and hydrology that may affect contaminant transport;
- The current and potential future uses of groundwater and exposure of receptors to other potentially impacted environmental media;
- The proximity of the site to drinking water aquifers, surface water, and other sensitive environmental resources;
- The expected persistence, mobility, chemical form, and fate of hazardous substances in the soil and groundwater under the influence of natural physical, chemical, and biological processes; and
- The treatability of residual and dissolved jet fuel contamination using low-cost source removal technologies such as bioventing.

It is the intent of the Air Force to pursue a site-specific risk-based remediation of Area D. Even though volatile and potential toxic pollutants, as defined by the SDDENR, were detected in soil and measured in groundwater at concentrations above

SDDENR promulgated standards, a site-specific risk analysis demonstrates that existing site contamination does not pose a risk to current or future onsite workers on the basis of site-specific exposure assumptions, and will not contribute to further degradation of groundwater quality. This analysis also shows that no exposure pathway to offsite receptors has been or will be completed. A quantitative assessment of the expected effectiveness of the recommended remedial action suggests that groundwater quality standards specified by SDDENR can be achieved at every point at the site within 30 years. In the interim, a perimeter of operational pollution will be established and annual monitoring will be conducted at the POA to ensure that site contaminants are decreasing in mass and toxicity and are not migrating offsite at concentrations above promulgated standards beyond the area under reliable exposure controls.

1.1.1 Summary of Proposed Type of Cleanup

The Air Force intends to implement a risk-based remedial action at Area D that is sufficient to minimize contaminant migration and eliminate potential risks to human health and the environment. This type of remedial action is consistent with the new site classification developed by SDDENR (1994) called inactive status. According to the SDDENR (1994), sites classified as inactive may be contaminated above state standards but contaminant levels are not increasing and do not pose a significant health or environmental threat. If a site is classified as inactive, no additional monitoring or active remediation will be required at the site. The proposed remedial action must be sufficient to prevent site-related contaminants from migrating at concentrations above state standards to areas beyond appropriate exposure controls. It also is possible that state promulgated groundwater quality standards (Chapter 74:03:15) could be fully achieved at the site over time. However, meeting these state standards at every point in the impacted area is neither a requirement or goal of this RAP if it is not necessary to protect human health and the environment.

The site characterization data presented in this RAP show that individual volatile and PAH compounds are present in soil (Chapter 74:03:32) and were measured in groundwater at concentrations above state standards (Chapter 74:03:15). A small pocket of light nonaqueous-phase liquid (LNAPL) may exist at the site, which could be acting as a continuous source of groundwater contamination. Measurable LNAPL was only found in MW-6 during the 1994 risk-based site investigations and during the baildown test conducted in October 1995 (see Figure 1.1). No measurable LNAPL was found in any of the monitoring wells or recently-installed leak detection wells within 80 feet of MW-6, which suggests that any persistent LNAPL is isolated in lateral extent at the site. A sample of LNAPL recently collected at MW-6 at the site had the chemical characteristics of fresh (i.e., unweathered) JP-4 jet fuel, indicating that there may be a small leak in an adjacent fuel transfer line. However, a recent baildown test suggests that little recoverable free product exists in the vicinity of MW-6. Consequently, although chemical analysis of the free product in MW-6 indicated that the product may be "fresh" and/or little weathering has occurred, no significant LNAPL plume appears to exist at the site. Remediation of any recoverable LNAPL using a passive recovery technology has been incorporated into the proposed remedial action for Area D.

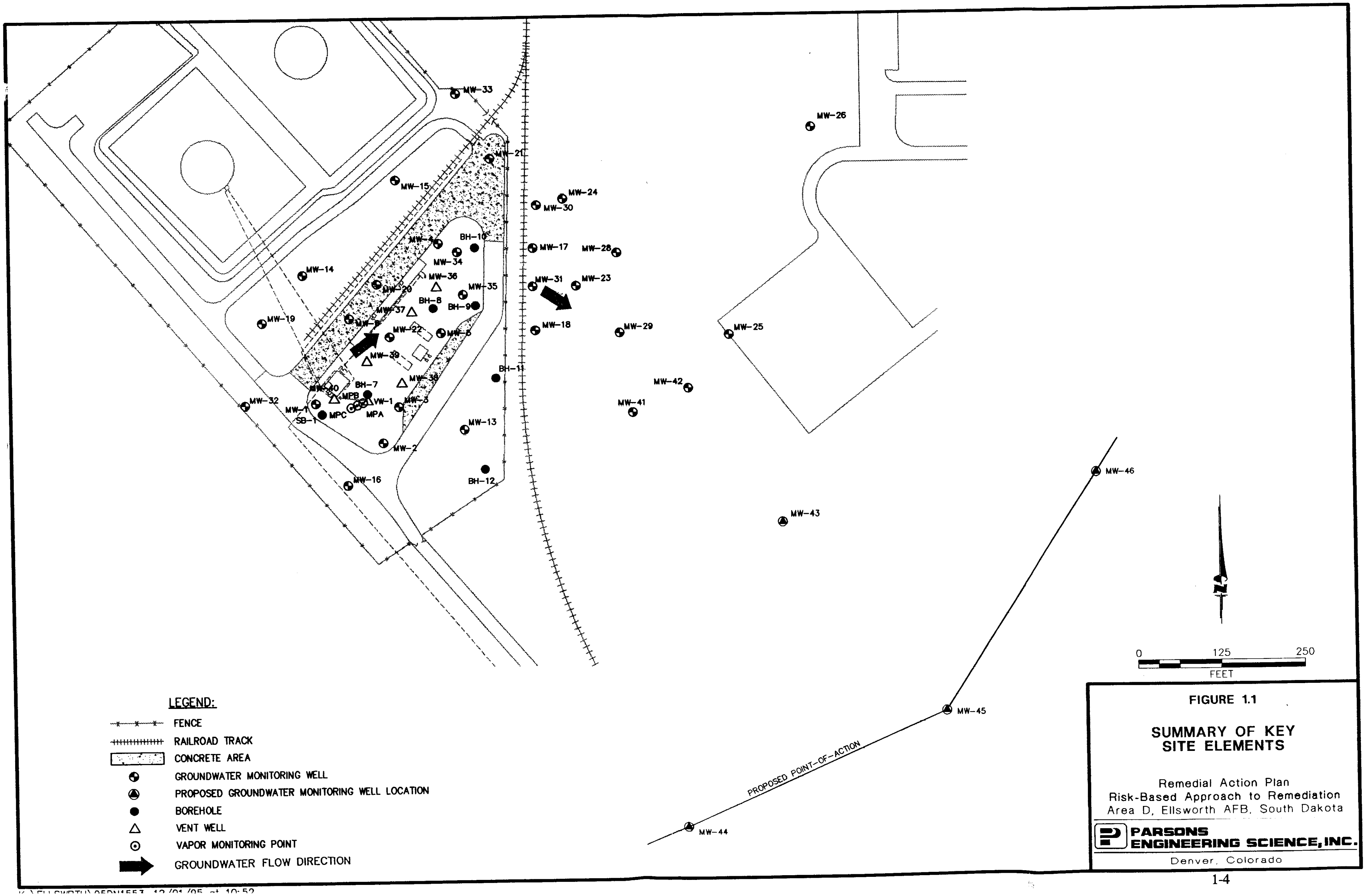

FIGURE 1.1

SUMMARY OF KEY SITE ELEMENTS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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The analysis conducted during this effort and included in this RAP indicates that concentrations of dissolved contaminants in groundwater at and downgradient from Area D do not and will not pose an unacceptable risk to human health or the environment. Existing concentrations of dissolved contaminants do not pose an unacceptable risk to current and potential future onsite workers or offsite receptors because no completed exposure pathway exists. Provided the leak is eliminated, no increase in contaminant concentrations in groundwater is expected to occur over time. Only minimal contaminant migration is anticipated due to natural physical, chemical, and biological processes which are effectively attenuating contaminants.

A quantitative fate and transport model (using the Bioplume II code) developed specifically for Area D demonstrates that dissolved contaminants will not migrate beyond the proposed POA at the southern and eastern edges of the large field to the east and southeast of the site. This proposed POA is more than 1 mile upgradient from the nearest on-Base residential area and approximately 2 miles upgradient from the nearest downgradient Base boundary (see Figure 1.1). An assessment of the effects of natural physical, chemical, and biological processes operating at the site suggests that, without engineered activities, these processes will be sufficient to prevent fuel contaminant concentrations above state standards from migrating to and beyond the proposed POA.

Supplementing these natural processes with passive recovery of free product, bioventing of contaminated soils, and a passive interceptor trench system to capture groundwater and route it to an air sparging treatment facility are options that were evaluated in this study and are discussed in Sections 7 and 8. The remedial alternative evaluation presented in this RAP indicates that the site could be a candidate for inactive status, as defined by the SDDENR (1994), within about 20 years provided adequate engineered actions are implemented to significantly reduce the LNAPL and soil contaminant sources at the site. Once classified as an inactive-status site, it would be unnecessary for the Air Force to undertake additional remedial action, including monitoring, at Area D even if contaminants were present at concentrations above state standards. Long-term compliance monitoring is proposed to support efforts to classify Area D as an inactive-status site, in accordance with SDDENR (1994) requirements. Long-term compliance monitoring is a necessary element of the proposed remedial action to confirm that the predicted degree of remediation is being attained.

1.2 SITE BACKGROUND

Ellsworth AFB is located approximately 12 miles east of Rapid City, South Dakota (Figure 1.2). The northern portion of the Base is located in Meade County, and the southern portion is located in Pennington County. Area D, a petroleum, oil, and lubricant (POL) tank farm, is the primary fuel storage and distribution center for aircraft fueling operations at the Base. The site is located in the central portion of the Base, to the east of the north hanger complex. Figure 1.3 shows the location of Area D on Ellsworth AFB.

Area D consists of two aboveground fuel storage tanks (ASTs) with a combined capacity of 90,000 barrels (bbl), two 25,000-gallon USTs, a 1,500-gallon UST, a

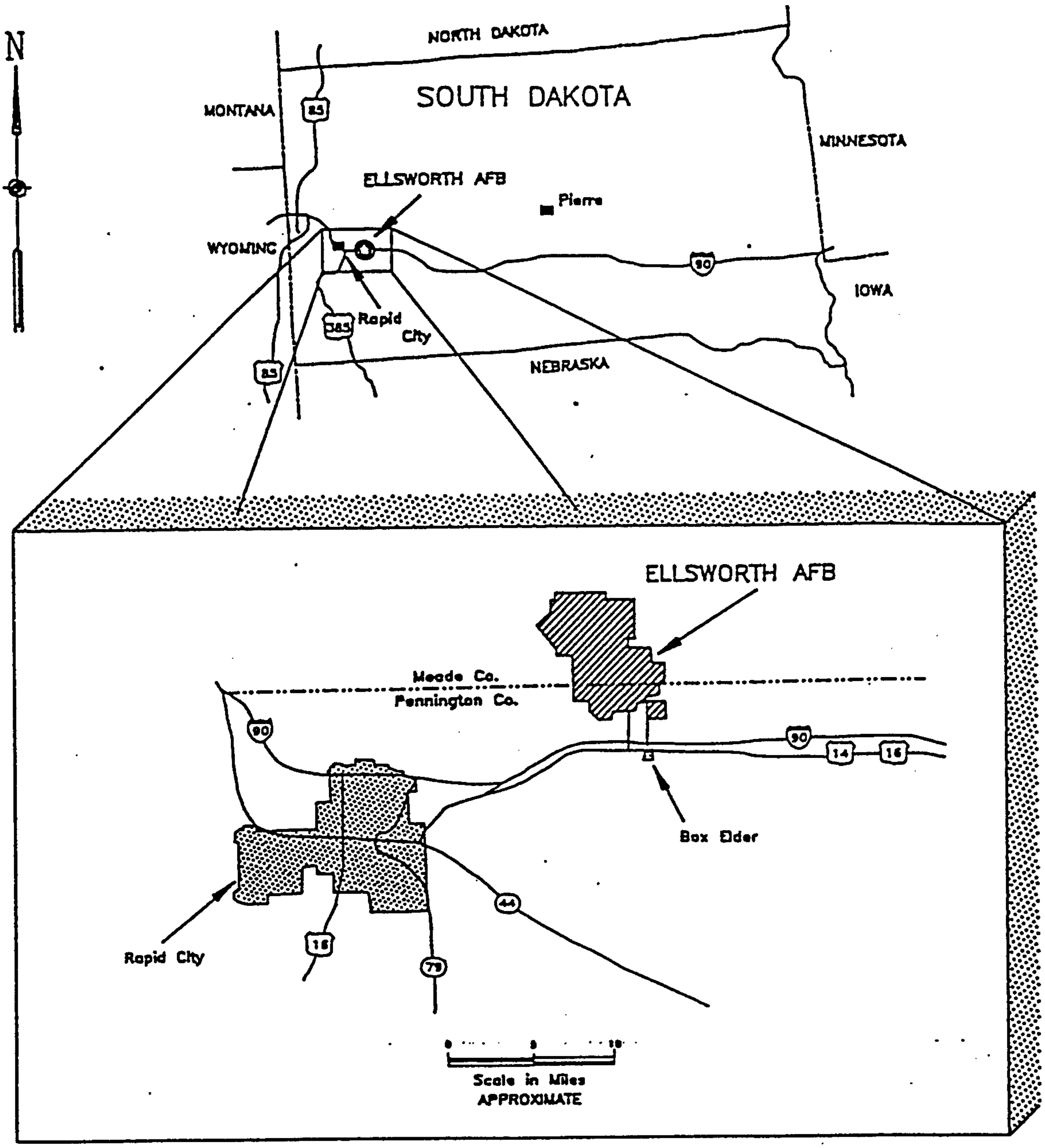

FIGURE 1.2

REGIONAL LOCATION OF ELLSWORTH AFB

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Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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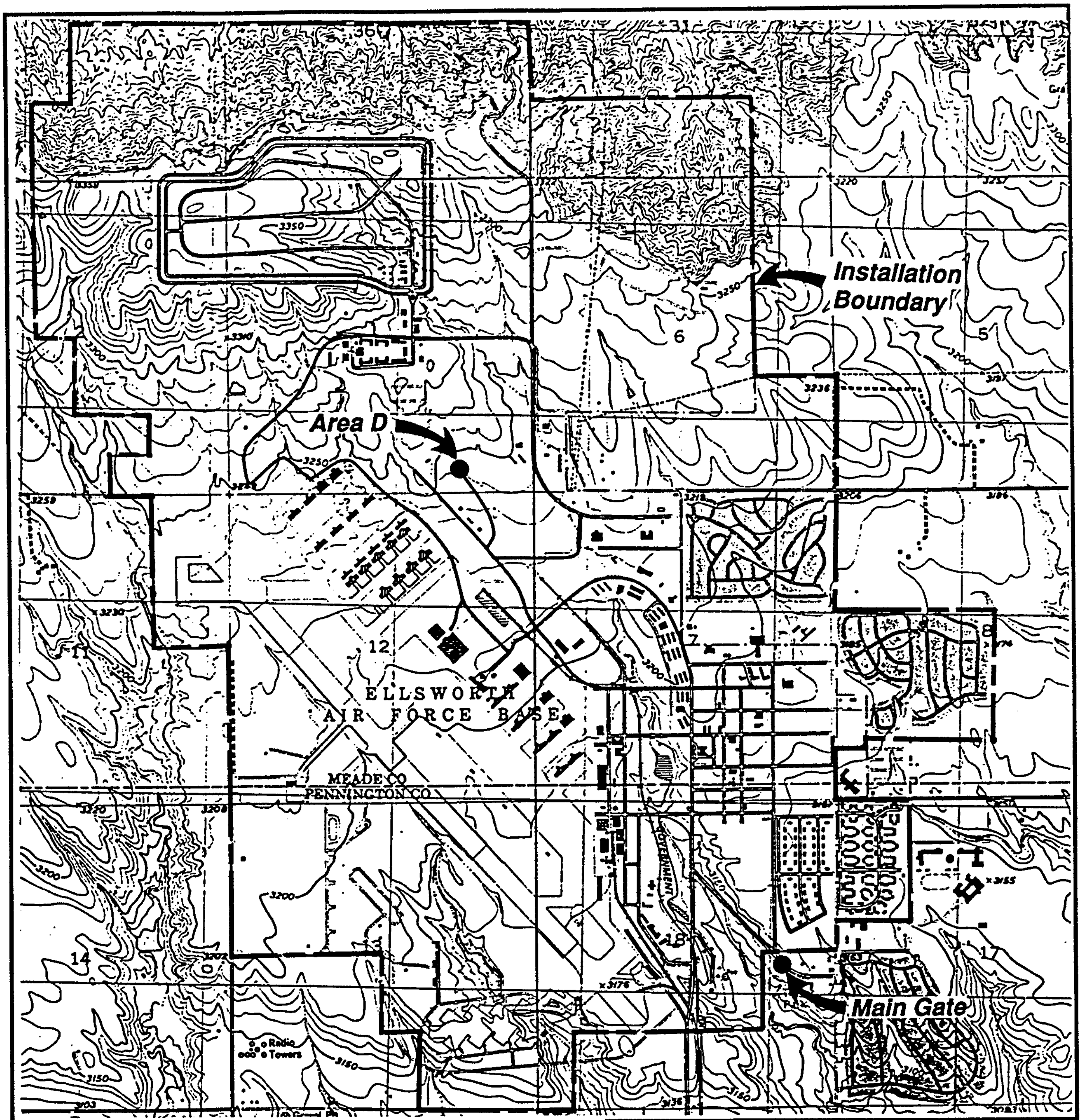

Source: USGS, Photorevised 1978.

FIGURE 1.3

LOCATION OF AREA D

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Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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1,000-gallon UST, two JP-4 jet fuel dispensers, and a railroad spur with fuel unloading headers (Figure 1.4). Currently the ASTs contain JP-4 jet fuel, the large USTs contain gasoline and diesel fuel, and the two smaller tanks are used as holdover and off-specification fuel tanks, respectively. The Base plans to begin using JP-8 fuel as a substitute for JP-4 in 1995. Fuels can be unloaded by three different systems. Bulk fuels can be unloaded from rail tank cars, from conventional tanker trucks, or via an underground pipeline from another tank farm, Area C, located at the southern edge of the Base (ES, 1993a). Currently, the railroad system is inactive, and fuels are delivered by truck only when the pipeline is taken out of service for repairs or maintenance.

1.2.1 Operational History

On September 11, 1990, after a failed system pressure test at Area D, the SDDENR was notified of a possible release. Following release notification, FMG, Inc. (FMG, 1991 and 1992) of Rapid City, South Dakota, was contracted to perform a fuel spill contamination survey at Area D. During the two phases of this investigation, 18 monitoring wells (MW-1 through MW-6 and MW-13 through MW-24) were installed and sampled, and 6 borings (BH-7 through BH-12) were drilled and sampled in the vicinity of Area D. Volatile hydrocarbon contamination was found in soil and groundwater within and downgradient from Area D.

In August 1993, a pilot-scale bioventing system was installed at the site by ES (1993a) as part of a nationwide effort sponsored by AFCEE to test and evaluate bioventing of fuel-contaminated soils. The pilot-scale bioventing system was operated for 1 year to determine the effectiveness of *in situ* bioventing in remediating hydrocarbon contamination in vadose zone soils at Area D. Results of this testing are presented in Section 7 of this RAP.

A multi-well leak detection system was installed at Area D in 1995 to monitor for any additional releases of fuel to the subsurface. Area D is still operational, and no other remedial actions have been taken at the site to date.

1.2.2 Previous Remedial Investigations

The entire Base has been qualitatively characterized in preparation for full-scale remedial investigations/feasibility studies (RI/FSs) (EA, 1994). Area D has been characterized under a two-phase fuel spill contamination survey (FMG, 1991 and 1992) and as part of the bioventing pilot test program sponsored by AFCEE (ES, 1993a). Some preliminary field work for the risk-based field test was performed during April 1994, while ES personnel were at the site to monitor the bioventing pilot test.

Analytical results on the soil samples collected during the 1991/1992 fuel spill survey indicated that detected concentrations of volatile compounds were limited to the southeastern grassy area bounded by paved access roads at the site (Figure 1.4). Based on the 1991/1992 soil analytical data, an area approximately 360 feet in length and 150 feet in width may be impacted by fuel contamination.

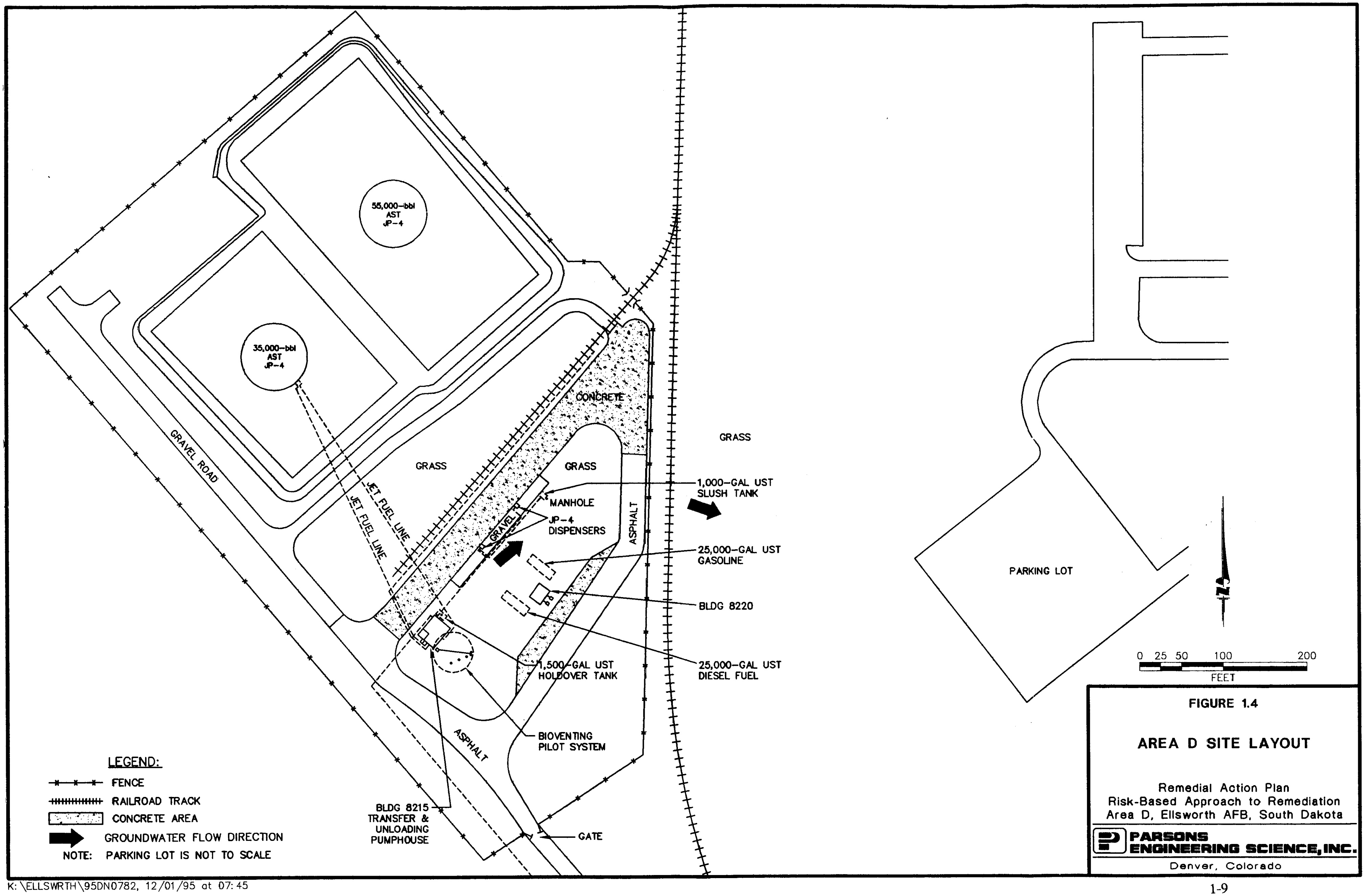

FIGURE 1.4

AREA D SITE LAYOUT

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Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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Concentrations of benzene, toluene, ethylbenzene, and total xylenes (total BTEX) in soil in 1991 and 1992 ranged from not detected (<0.2) to 98.4 milligrams per kilogram (mg/kg). Although no benzene was detected at concentrations above the reported detection limit in any soil sample collected during the fuel spill survey conducted by FMG (1991 and 1992), toluene, ethylbenzene, and total xylenes were detected in soil samples. Toluene concentrations ranged from less than 0.2 to 17 mg/kg; ethylbenzene concentrations ranged from less than 0.2 to 18 mg/kg; and total xylenes concentrations ranged from less than 0.2 to 81 mg/kg (FMG, 1991 and 1992). Because fuel contamination was found in samples taken from the surface, or near surface, to a depth of approximately 26.5 feet below ground surface (bgs) at the site, multiple contamination sources such as surface fuel spills, tank overfilling, and leaking underground fuel transfer lines are suspected.

Although each of the volatile BTEX compounds was detected in groundwater during the 1991/1992 fuel spill survey, benzene was the only compound measured at concentrations above the SDDENR groundwater quality standard of 5 micrograms per liter (μg/L). The maximum lateral extent of detected total BTEX compounds was estimated during this investigation to be about 350 feet (FMG, 1991 and 1992). However, data on hydrogeological characteristics collected as part of the 1994 risk-based investigation indicates that the dissolved plume may not have been fully characterized in 1991/1992.

The maximum concentration of total BTEX measured in groundwater at the site during the 1991/1992 fuel spill survey was 4,163 μg/L at MW-20, which is located immediately adjacent to and downgradient from a JP-4 dispenser (Figure 1.4). Benzene was detected at a concentration of about 2,675 μg/L at MW-20 and at a concentration of 440 μg/L at MW-4, which is about 110 feet downgradient from MW-20. Benzene also was detected at concentrations of 10 μg/L at MW-1 and 0.8 μg/L at MW-2 (FMG, 1991 and 1992). All detected concentrations of benzene in groundwater at the site in 1991/1992 except for MW-2 were above the SDDENR groundwater quality standard of 5 μg/L. Although toluene was detected in groundwater samples collected during the fuel spill survey, no concentrations above the SDDENR groundwater quality standard of 1,000 μg/L were measured. The maximum concentration of ethylbenzene measured in groundwater at the site in 1991/1992 was 659 μg/L at MW-20, which is slightly less than the SDDENR groundwater quality standard of 700 μg/L. The maximum concentration of total xylenes in groundwater in 1991/1992 was 817 μg/L at MW-20, which is more than an order of magnitude less than the SDDENR groundwater quality standard of 10,000 μg/L. No groundwater samples were analyzed for other organic compounds, including PAHs or chlorinated solvents, as part of the fuel spill survey (FMG, 1991 and 1992).

Soil samples were collected at the site in August 1993 at three locations near the bioventing pilot test system to establish baseline volatile compound concentrations for the year-long pilot test. Concentrations of total BTEX measured in soil at this time were significantly greater than those reported by FMG (1991 and 1992). Total BTEX concentrations ranged from 80.9 to 382 mg/kg (ES, 1993a). Total xylenes accounted for between 70 and 80 percent of the total BTEX in the contaminated soils sampled in

August 1993. No groundwater samples were collected during the pilot bioventing system test.

Confirmatory soil samples were collected at the same three locations after the bioventing system had been in operation for 1 year. Concentrations of BTEX measured in soil were much lower than initial values, indicating that bioventing can successfully bioremediate BTEX in unsaturated soils at Area D. Total BTEX concentrations from the three samples collected from the pilot test area ranged from 0.759 mg/kg to 24.82 mg/kg in August of 1994. These results are discussed in more detail in subsequent sections of this RAP.

MW-6 is the only well in which LNAPL has been encountered. Variable levels of LNAPL have been measured in this well since early 1992. The Phase II report (FMG, 1992) states that three additional wells (i.e., MW-19, MW-20, and MW-22) were installed on January 13, 1992, to further delineate free-phase product discovered in MW-6. No product was measured in 1992 or 1994 in any of these three wells. No product was measured in any of the recently-installed leak detection wells in 1995.

FMG (1992) also reported evidence of residual LNAPL in MW-4 and BH-10 during drilling and well installation activities that took place in October 1991. Yet after well development, mobile LNAPL was not evident in MW-4. BH-10 was not completed as a well (FMG, 1991). Parsons ES found MW-4 to be collapsed and filled with sand during the 1994 investigation. Further details on the physical characteristics of Area D and the probable nature and extent of subsurface fuel hydrocarbon contamination are presented in subsequent sections of this RAP.

The focused site investigation and remedial alternatives analysis described in this RAP were designed to evaluate and recommend the type and magnitude of remedial action necessary to protect human health and the environment at and downgradient from Area D. This RAP specifically documents the effects of natural physical, chemical, and biological processes and low-cost source reduction technologies on contaminant persistence, mobility, mass, and toxicity over time and distance at the site.

1.3 REPORT ORGANIZATION

This RAP consists of 10 sections, including this introduction, and 9 appendices. Section 2 summarizes the site characterization activities performed by Parsons ES. Physical characteristics of Area D and the nature and extent of soil and groundwater contamination are described in Sections 3 and 4, respectively. Section 5 presents the proposed cleanup objectives and requirements for the site. Section 6 documents the effects of natural physical, chemical, and biological processes on site-related contaminants, and summarizes predictions of how these processes will affect soil and groundwater contamination over time. Section 7 presents contaminant treatability pilot test results and evaluates source removal technologies. A comparative analysis of three candidate remedial alternatives is discussed in Section 8. Section 9 is a detailed implementation plan for the recommended remedial alternative. A site-specific long-term monitoring plan is presented in Section 10.

Appendix A presents soil, groundwater, soil gas flux test, and soil gas analytical results and data validation results. Appendix B contains the borehole logs, well construction diagrams, and well development data for sampling activities completed in 1994. Aquifer test data and analyses are presented in Appendix C. Appendix D presents the data and results obtained from a geophysical survey at the site. Appendix E contains quantitative calculations relevant to documenting the effectiveness of naturally occurring physical, chemical, and biological processes on reducing the mass, mobility, and toxicity of site-related contaminants. Appendix F contains source reduction feasibility testing data and calculations. Appendix G contains risk-based cleanup level calculations and chemical profiles for each chemical evaluated as part of this RAP. Appendix H summarizes the screening, development, and cost estimation of remedial alternatives considered in detail within this RAP. Appendix I presents a site-specific sampling and analysis plan (SAP) for use during long-term monitoring at the site.

SECTION 2

SITE CHARACTERIZATION ACTIVITIES

To fully characterize the nature and extent of fuel hydrocarbon contamination at and downgradient from Area D and collect site-specific data documenting the effects of natural contaminant attenuation processes, a field investigation was conducted by Parsons ES at Area D from August through October 1994. A baildown test was conducted at the site exactly one year later (October 1995) to evaluate the feasibility of product recovery techniques. Sufficient data were collected to conduct a quantitative fate and transport analysis, perform an exposure pathway analysis, and evaluate the potential treatability of contaminated media using low-cost remedial technologies and approaches. Emphasis was placed on filling data gaps identified during previous investigations and on collecting data relevant to documenting the biodegradation of fuel hydrocarbons in soil and groundwater.

2.1 SCOPE OF DATA COLLECTION ACTIVITIES

The field investigation focused on collecting data on the specific chemical constituents that may drive potential risks and impact the final remedial design for Area D. The chemicals of potential concern (COPCs) for Area D were identified based on results of the fuel spill survey (FMG, 1991 and 1992) and the chemical composition of the suspected source, which is a release of JP-4 jet fuel into soils and groundwater from a leaking UST and/or fuel transfer lines. JP-4, a turbine fuel used exclusively by the US Air Force, is composed of the hydrocarbon fraction that distills in the 140-degrees-Celsius (°C) to 270°C range. The fuel is predominantly a mixture of C_4 through C_{14} hydrocarbons. The major component categories (and their percentages by weight) in JP-4 are n-alkanes (32 percent), branched alkanes (31 percent), cycloalkanes (16 percent), benzenes and alkylbenzenes (18 percent), and naphthalenes (3 percent).

On the basis of the environmental behavior of each group of specific hydrocarbons and the results of previous site investigation activities at Area D, the COPCs identified and addressed as part of this demonstration included the BTEX compounds and naphthalene. All analytical data collected on these COPCs were obtained using fixed-base analytical methods performed by Evergreen Analytical, Inc., located in Wheat Ridge, Colorado. Field and other fixed-base analytical data relevant to documenting biodegradation and assessing the effectiveness of low-cost source removal technologies also were collected.

The investigation activities completed at Area D during the risk-based remediation demonstration were conducted using the approach and methodologies presented in the *Final Work Plan for an Engineering Evaluation/Cost Analysis in Support of the Risk-*

Based Approach to Remediation at Area D (ES, 1994a) (hereafter referred to as the work plan). The following sampling and testing activities were performed by Parsons ES at Area D as part of this demonstration:

- One-year sampling and evaluation of the pilot-scale *in situ* bioventing remediation system;
- Baildown testing of MW-6 as the first step toward evaluating the feasibility of free product recovery;
- Collection of soil gas samples at 4 locations;
- Collection of soil gas flux samples at 4 locations;
- Drilling and installation of 18 additional groundwater monitoring and bioventing air injection wells;
- Collection of 21 discrete subsurface soil samples from 16 soil boreholes for field screening and fixed-base analytical evaluation;
- Field screening and sampling for chemical parameters relevant to documenting fuel hydrocarbon biodegradation in 32 groundwater monitoring wells;
- Collection of 21 groundwater samples for laboratory analysis from 20 groundwater monitoring wells;
- Aquifer slug testing at 9 groundwater monitoring wells; and
- Seismic refraction survey to determine bedrock elevation.

Figure 2.1 shows the locations of the soil gas and soil gas flux sampling points. Figure 2.2 shows the location of the boreholes from which subsurface soil samples were collected during this field investigation. Figure 2.3 identifies all sampling locations used to characterize groundwater quality in 1994. A descriptive summary of all of the field and fixed-base analytical methods used at Area D is presented in Table 2.1, per Section V of the SDDENR (1994) handbook. The program-specific method detection limits (MDLs) for all analytical methods used to measure COPCs are equal to or below those recommended by SDDENR in Chapters 74:03:32:04 and 74:03:15:05. The MDL is the lowest concentration at which a chemical can be measured and distinguished with 99-percent confidence from the normal "noise" of an analytical instrument or method. Table 2.1 also lists the practical quantitation limits (PQLs) for each analytical method by analyte and environmental medium. The PQL is the lowest level at which a chemical can be accurately and reproducibly quantitated.

Table 2.2 summarizes the field and fixed-base analytical methods used at each sampling location. Field sampling and testing activities are summarized briefly in the following sections.

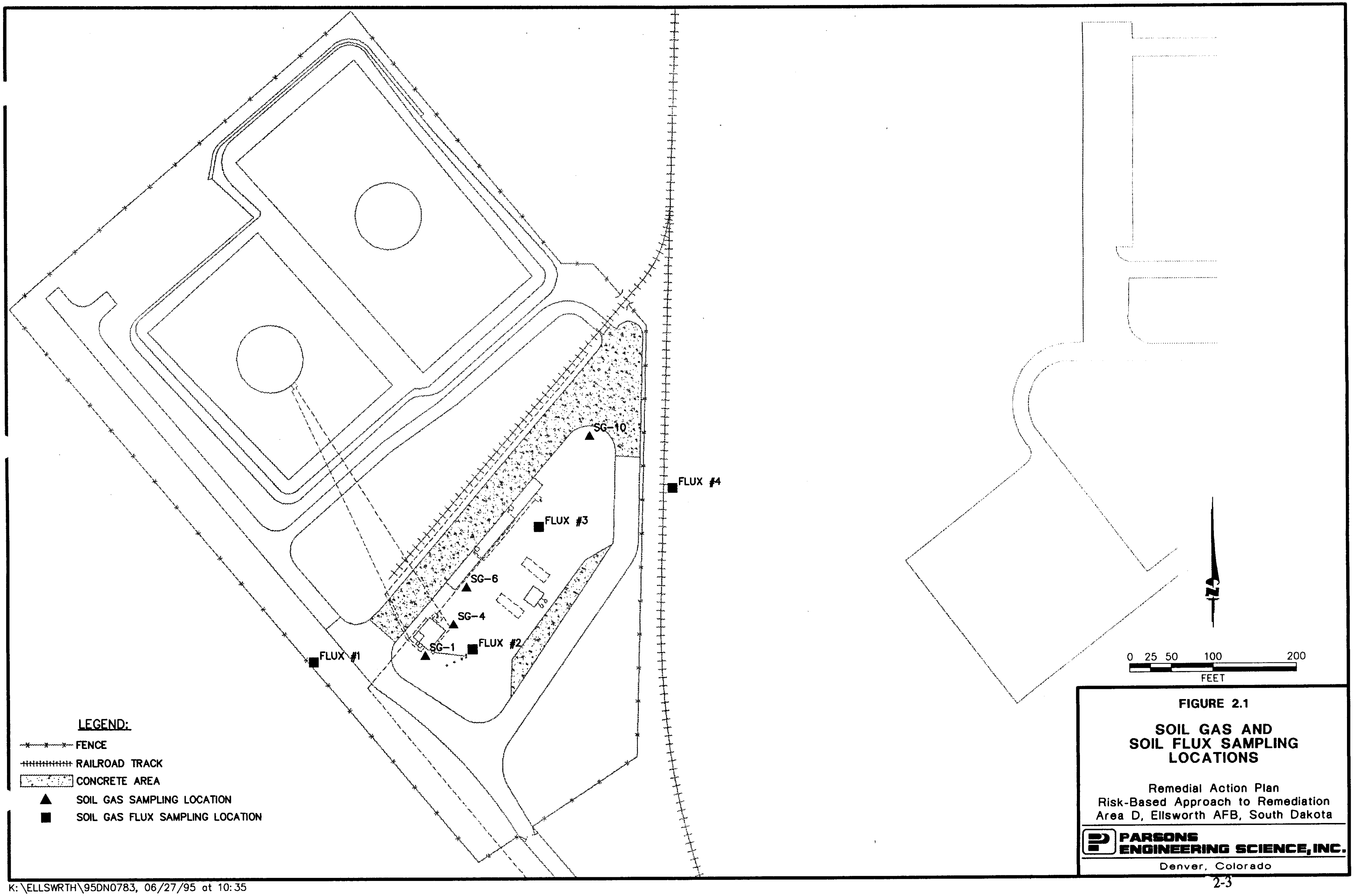

FIGURE 2.1

SOIL GAS AND
SOIL FLUX SAMPLING
LOCATIONS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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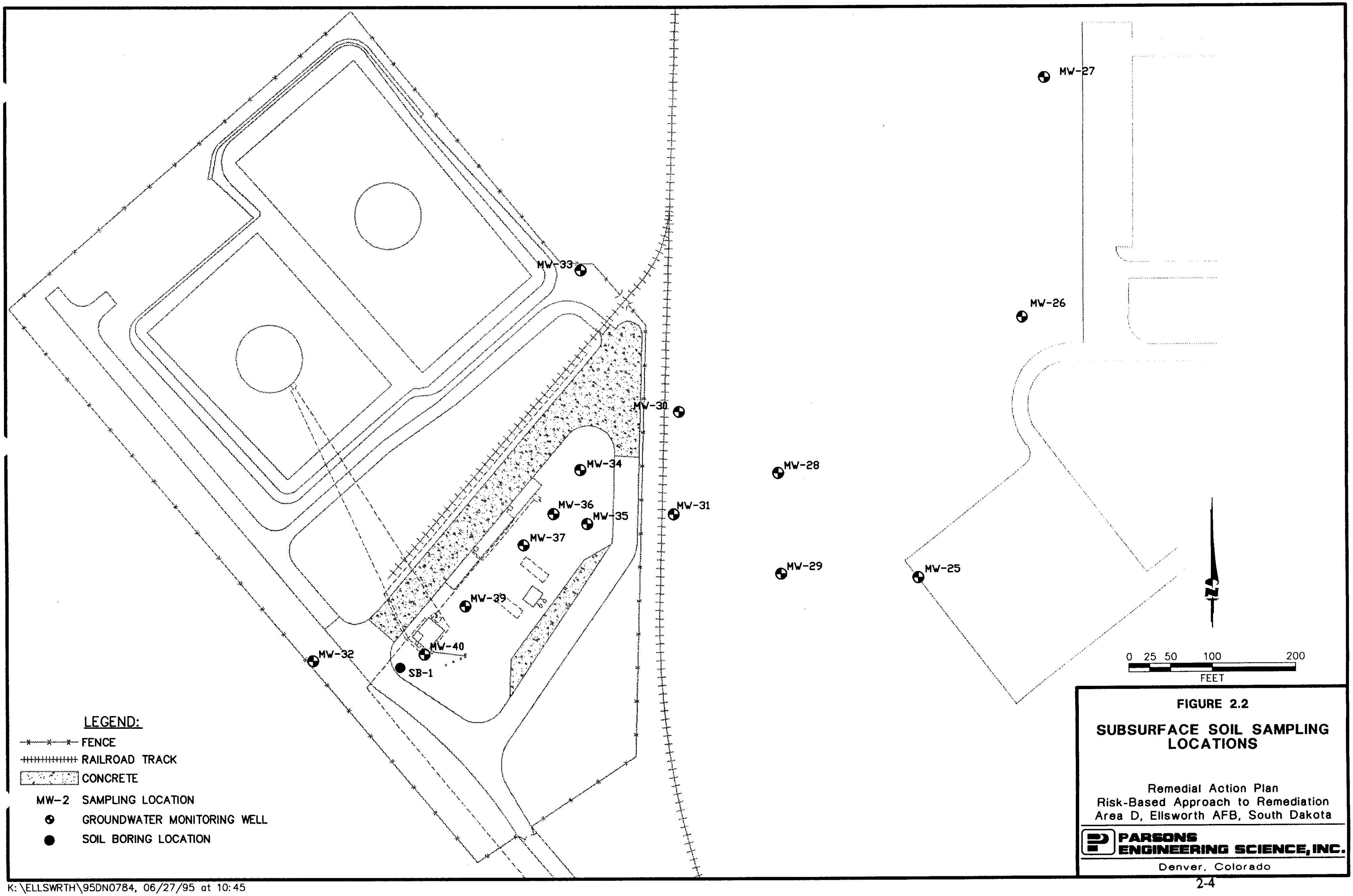

FIGURE 2.2

SUBSURFACE SOIL SAMPLING LOCATIONS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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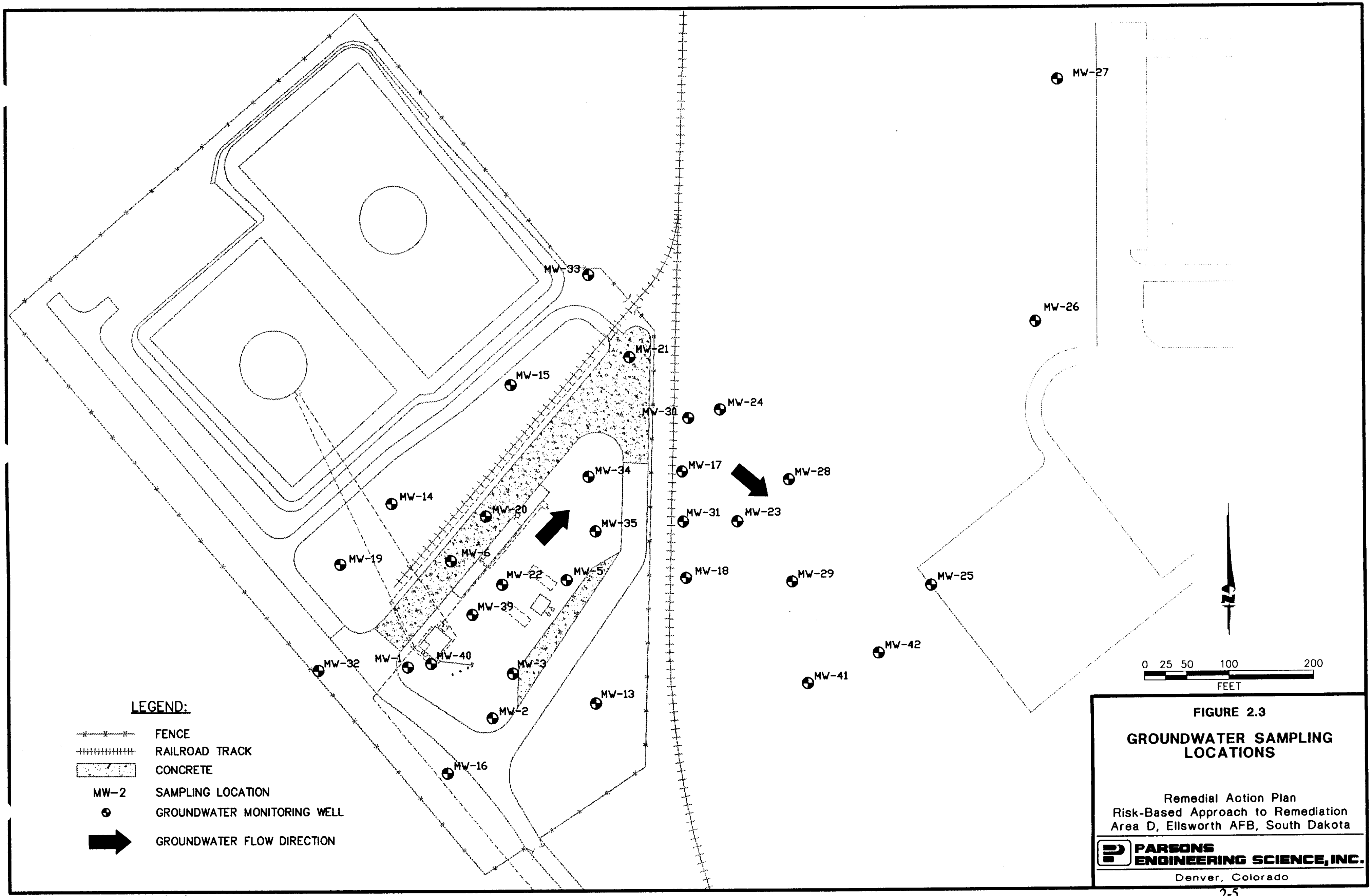

FIGURE 2.3

GROUNDWATER SAMPLING LOCATIONS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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ANALYTE REPORTING LIMITS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte	Analytical Method	Field or Fixed-Base	Soil Gas MDL	Soil Gas Units	Site-Specific Soil MDL	Soil Reporting Limit[a/]	Soil Units	Site-Specific Water MDL	Water Reporting Limit[a/]	Water Units
SOIL GAS										
Benzene	TO3	Fixed-Base	1.00E-03	ppmv						
Toluene	TO3	Fixed-Base	1.00E-03	ppmv						
Ethylbenzene	TO3	Fixed-Base	1.00E-03	ppmv						
Xylene (Total)	TO3	Fixed-Base	1.00E-03	ppmv						
Total Volatile Hydrocarbons (TVH)	TO3	Fixed-Base	1.00E-02	ppmv						
SOIL AND GROUNDWATER										
TEH as Jet Fuel	M8015	Fixed-Base			NR[b/]	1.00E+01	mg/kg	5.22E-01	5.00E+02	µg/L
TVH as Gasoline	M8015	Fixed-Base			6.00E-03	1.00E-01	mg/kg	8.90E-02	1.00E+02	µg/L
Benzene	SW8020/E602	Fixed-Base			2.83E-01	4.00E-01	µg/kg	2.83E-01	4.00E-01	µg/L
Toluene	SW8020/E602	Fixed-Base			2.57E-01	4.00E-01	µg/kg	2.57E-01	4.00E-01	µg/L
Ethylbenzene	SW8020/E602	Fixed-Base			2.83E-01	4.00E-01	µg/kg	2.83E-01	4.00E-01	µg/L
Xylene (Total)	SW8020/E602	Fixed-Base			2.47E-01	4.00E-01	µg/kg	2.47E-01	4.00E-01	µg/L
Chlorobenzene	SW8020/E602	Fixed-Base			2.83E-01	4.00E-01	µg/kg	2.83E-01	4.00E-01	µg/L
1,2,3,4-Tetramethylbenzene	SW8020/E602	Fixed-Base			NR[b/]	5.00E-01	µg/kg	NR	5.00E-01	µg/L
1,2,3-Trimethylbenzene	SW8020/E602	Fixed-Base			1.53E-01	4.00E-01	µg/kg	1.53E-01	4.00E-01	µg/L
1,2,4-Trimethylbenzene	SW8020/E602	Fixed-Base			1.68E-01	4.00E-01	µg/kg	1.68E-01	4.00E-01	µg/L
1,3,5-Trimethylbenzene	SW8020/E602	Fixed-Base			1.68E-01	4.00E-01	µg/kg	1.68E-01	4.00E-01	µg/L
Naphthalene	SW8270	Fixed-Base			5.00E-01	3.30E+02	µg/kg	5.00E-01	1.00E+01	µg/L
SOIL ONLY										
Iron	SW6010	Fixed-Base			3.20E-02	1.60E+00	mg/kg			
Alkalinity, Total (as $CaCO_3$)	E310.1	Fixed-Base			NR	2.50E+01	mg/kg			
Phosphorous, Total Orthophosphate (as P)	E300	Fixed-Base			5.10E-01	2.50E+00	mg/kg			
Moisture, percent	E160.3	Fixed-Base			NR	1.00E-01	percent			
Nitrogen, Total Kjeldahl	E351.2	Fixed-Base			5.00E+00	5.00E+00	mg/kg			
pH	SW9045	Fixed-Base			NR	1.00E-02	pH units			
Total Organic Carbon	SW9060	Fixed-Base			1.50E-02	5.00E-02	%			
GROUNDWATER ONLY										
Benzene	SW8240	Fixed-Base						5.00E-01	5.00E+00	µg/L
Toluene	SW8240	Fixed-Base						5.00E-01	5.00E+00	µg/L
Ethylbenzene	SW8240	Fixed-Base						5.00E-01	5.00E+00	µg/L
Xylene (Total)	SW8240	Fixed-Base						5.00E-01	5.00E+00	µg/L
Chlorobenzene	SW8240	Fixed-Base						1.00E+00	5.00E+00	µg/L
Styrene	SW8240	Fixed-Base						1.00E+00	5.00E+00	µg/L
1,2,3,4-Tetramethylbenzene	SW8240	Fixed-Base						1.00E+00	5.00E+00	µg/L

TA 2.1
ANALYTE REPORTING LIMITS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte	Analytical Method	Field or Fixed-Base	Soil Gas MDL	Soil Gas Units	Site-Specific Soil MDL	Soil Reporting Limit[a/]	Soil Units	Site-Specific Water MDL	Water Reporting Limit[a/]	Water Units
1,2,3-Trimethylbenzene	SW8240	Fixed-Base						1.00E+00	5.00E+00	µg/L
1,2,4-Trimethylbenzene	SW8240	Fixed-Base						1.00E+00	5.00E+00	µg/L
1,3,5-Trimethylbenzene	SW8240	Fixed-Base						1.00E+00	5.00E+00	µg/L
Electrical Conductivity	FCOND	Field						NR	2.00E-02	mmhos/cm
Dissolved Oxygen	FDO	Field						NR	5.00E-01	mg/L
pH	FPH	Field						NR	1.00E-01	pH Units
Redox Potential	FREDOX	Field						NR	1.00E-02	pE Units
Temperature	FTEMP	Field						NR	1.00E+00	° C
Nitrate	H8039	Field						1.00E-02	6.60E-02	mg/L
Nitrite	H8040	Field						5.00E-03	1.00E-02	mg/L
Sulfate	H8051	Field						1.00E-02	1.00E-02	mg/L
Sulfide	H8131	Field						1.00E-02	2.40E-02	mg/L
Iron, Ferrous	H8146	Field						1.00E-02	2.40E-02	mg/L
Iron, Total	H8008	Field						1.00E-02	2.40E-02	mg/L
Alkalinity (as $CaCO_3$)	H8221	Field						2.00E+01	2.00E+01	mg/L
Carbon Dioxide	H8223	Field						1.00E-02	1.25E+00	mg/L
Manganese	HMANG	Field						1.00E-02	5.00E-02	mg/L
Carbon Dioxide	COU-O2	Fixed-Base						NR	5.00E+00	mg/L
Methane	RSK175	Fixed-Base						4.00E-03	4.00E-03	mg/L

[a/] Most of these reporting limits are equal to the pratical quantitation limit (PQL);
In some cases, the reporting limit is equal to the reliable detection limit (RDL).

[b/] NR = Detection limit not required/developed for this analyte.

TABLE 2.2
SAMPLE ANALYSIS BY SAMPLING LOCATION
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
ELLSWORTH AFB, SOUTH DAKOTA

SAMPLING LOCATION	NORTHING	EASTING	SAMPLE MATRIX	SAMPLE DEPTH (ft. bgs)	ANALYTES											
					BTEX	PAH	TVH/ TEH	ELECTRON ACCEPTORS	PHOS	ALK	CO_2	CH_4	MOISTURE	GRAIN SIZE	SOIL pH	SOIL TOC
SC-1-1	NS[a]	NS	Drill Cuttings	NA	1[b]		X									
SC-1-2	NS	NS	Drill Cuttings	NA	1		X									
SC-2-1	NS	NS	Drill Cuttings	NA	1		X									
SC-2-2	NS	NS	Drill Cuttings	NA	1		X									
MW-1	1132932.9	1156220.62	Groundwater	NA				X								
MW-2	1132873.02	1156321.82	Groundwater	NA				X								
MW-3	1132927.07	1156346.25	Groundwater	NA				X								
MW-5	1133037.11	1156411.66	Groundwater	NA				X								
MW-6	1133058.93	1156272.02	Groundwater	NA				X								
			Free Product	NA	1		X									
MW-13	1132889.86	1156445.45	Groundwater	NA	1			X								
MW-14	1133125.70	1156203.35	Groundwater	NA				X								
MW-15	1133266.27	1156353.76	Groundwater	NA	1			X								
MW-16	1132808.41	1156268.24	Groundwater	NA	1	X		X			X	X				
MW-17	1133162.91	1156552.13	Groundwater	NA				X								
MW-18	1133038.26	1156556.18	Groundwater	NA				X								
MW-19	1133054.50	1156141.31	Groundwater	NA				X								
MW-20	1132873.02	1156321.82	Groundwater	NA				X								
MW-21	1133111.12	1156315.69	Groundwater	NA				X								
MW-22	1133297.73	1156489.01	Groundwater	NA	1		X	X								
MW-23	1133032.28	1156333.91	Groundwater	NA				X								
MW-24	1133104.07	1156617.63	Groundwater	NA	1			X								
MW-25	1133028.15	1156848.79	Soil	14.5-15.5	1											
			Groundwater	NA	1		X	X			X	X				
MW-26	1133337.76	1156975.65	Soil	23.5-24.5	1		X								X	X
			Groundwater	NA	1			X								
MW-27	1133625.05	1157004.29	Soil	23.5-24.5	1											
			Groundwater	NA	1			X								
MW-28	1133152.89	1156679.69	Soil	18.5-19.5	1											
			Groundwater	NA	1			X								
MW-29	1133032.47	1156682.70	Soil	16.5-17.5	1		X									
			Groundwater	NA	1	X	X	X				X				
MW-30	1133225.67	1156559.52	Soil	19.5-20.5	1											
			Groundwater	NA	1			X								
MW-31	1133103.97	1156553.16	Soil	20.5-21.5	1		X								X	X
			Groundwater	NA	1	X		X								
MW-32	1132931.04	1156114.25	Soil	17.5-18.5	1											
			Groundwater	NA	1		X	X			X	X				
MW-33	1133394.99	1156440.29	Soil	22.5-23.5	1											
			Groundwater	NA	1			X								
MW-34	1133157.34	1156438.61	Soil	24.5-25.5	1											
			Soil	25.5-26.5											X	X
			Groundwater	NA	1		X	X			X	X				
MW-35	1133092.71	1156446.91	Soil	21.5-22.5	1		X									
			Groundwater	NA	1	X	X	X			X	X				
MW-36	1133105.64	1156404.67	Soil	21.5-22.5	1		X									
MW-37	1133069.03	1156370.13	Soil	21.5-22.5	1											
MW-39	1132995.23	1156299.34	Soil	14.5-15.5									X	X		
			Soil	18.5-19.5	1		X						X	X	X	X
			Groundwater	NA	1	X	X	X			X	X				
MW-40	1132937.18	1156248.88	Soil	13.5-14.5	1		X						X	X		
			Soil	17.5-18.5									X	X		
			Groundwater	NA	1	X										
MW-41	1132912.57	1156697.73	Groundwater	NA	1											
MW-42	1132950.38	1156786.20	Groundwater	NA	1											
SB-1	1132921.16	1156214.51	Soil	16.5-17.5	1											
MW-40	1132937.18	1156248.88	Soil	9.0-10.0	1											
MW-36	1133105.64	1156404.67	Soil	22.5-23.5	1		X									
FLUX1	NS	NS	Soil Flux	NA	2[c]											
FLUX2	NS	NS	Soil Flux	NA	2											
FLUX3	NS	NS	Soil Flux	NA	2											
FLUX4	NS	NS	Soil Flux	NA	2											
SG1	NS	NS	Soil Gas	NA	2											
SG4	NS	NS	Soil Gas	NA	2											
SG6	NS	NS	Soil Gas	NA	2											
SG10	NS	NS	Soil Gas	NA	2											

[a] NS = Not surveyed.
[b] 1 = SW8020: Purgeable Aromatics.
[c] 2 = TO3: Determination of Volatile Organic Compounds in Ambient Air.

2.2 SOIL GAS AND SOIL FLUX MEASUREMENTS

Soil gas sampling was performed to estimate the extent of subsurface soil contamination and to determine the potential for lateral and upward diffusion of contaminated soil gas at the site. The purpose of surface flux sampling was to measure any upward diffusion of the volatile COPCs from the soil into the atmosphere and potentially into buildings within or adjacent to Area D. These data are used to determine if the vapor inhalation pathway is complete.

2.2.1 Soil Gas Sampling

Soil gas samples were collected by ES in August 1994 from the four locations shown on Figure 2.1. Sample locations were determined based on an evaluation of previous data from the FMG (1991 and 1992) fuel spill survey. All soil gas samples were screened for fuel hydrocarbons, oxygen, and carbon dioxide using the test equipment and methods specified for field soil gas surveys in the AFCEE protocol documents *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing* (Hinchee *et al.*, 1992) and *Addendum One to Test Plan and Technical Protocol for a Field Treatability Test for Bioventing: Using Soil Gas Surveys to Determine Bioventing Feasibility and Natural Attenuation Potential* (Downey and Hall, 1994).

Soil gas samples were collected and analyzed using the fixed-base analytical US Environmental Protection Agency (EPA) Method TO-3 for specific volatile COPCs (i.e., the BTEX compounds) and total volatile hydrocarbons (TVH). Table 2.2 identifies the type of field and fixed-base analytical data collected at each soil gas sampling location. All sample handling and field quality assurance (QA)/quality control (QC) procedures for soil gas are specified in Appendix A of the work plan (ES, 1994a). Analytical results for soil gas samples are summarized in Section 4 and presented in tabular form in Appendix A of this RAP.

2.2.2 Soil Gas Flux Sampling

Four soil gas flux tests were performed at Area D by ES in August 1994 at the locations shown on Figure 2.1. Tests were performed at Area D to determine if soil contamination could potentially release volatile organic compounds (VOCs) into the atmosphere or nearby buildings and impact ambient air quality. Sampling points were located so that one sample was collected from a background area (i.e., an area upgradient from and presumably unaffected by site-related contamination), two from the suspected source area, and one from a downgradient area. Flux samples were collected at Area D using the equipment and procedures outlined in the EPA (1986) guidance document, *Measurement of Gaseous Emissions Rates from Land Surfaces Using a Emission Isolation Flux Chamber*. Samples were collected in a flux chamber and transferred to 1-liter SUMMA® canisters for laboratory BTEX and TVH analyses using EPA Method TO-3. If significant COPC emissions were measured, data from the flux chamber can then be combined with a simple dispersion model to identify potential ambient air quality impacts, as described in the work plan (ES, 1994a). All sample handling and field QA/QC procedures for soil gas are specified in Appendix A of the work plan (ES, 1994a). Analytical results for soil gas flux samples are summarized in Section 4 and presented in tabular form in Appendix A of this RAP.

2.3 SUBSURFACE SOIL SAMPLING

Subsurface soil samples were collected at Area D to further delineate the nature and extent of saturated and unsaturated soil contamination at the site. New soil boreholes were drilled with the goals of expanding the existing groundwater monitoring well network and collecting additional soil contaminant data. During the course of the field investigation at Area D, a total of 21 soil samples were collected from 16 borings. Thirteen of the borings were completed as 2-inch-diameter groundwater monitoring wells, five were completed as 4-inch-diameter bioventing air injection wells, and three boreholes were abandoned after sample collection. Three borings (MW-38, MW-41, and MW-42) could not be sampled because the presence of large cobbles in the subsurface precluded sample collection. Three soil samples also were collected by ES in August 1994 using a hydraulic push sampler. Soil boreholes resulting from this activity were abandoned immediately after sample collection.

Figure 2.2 shows the locations of all subsurface soil sampling locations. All drilling and subsurface soil sampling took place from September 12 through 26, 1994, and was accomplished using a hollow-stem auger (HSA) and following the procedures described in the work plan (ES, 1994a). These procedures are in accordance with the general procedures outlined in Section 8.5 of *A Compendium of Superfund Field Methods* (EPA, 1987). Samples were collected and handled as described in Appendix A of the work plan. QA/QC samples were also collected and analyzed in accordance with the work plan (ES, 1994a).

Table 2.2 presents the State of South Dakota state plane coordinates and sample depth interval for each of the subsurface soil sampling locations sampled as part of this demonstration at Area D. This table also lists the field and fixed-base analytical methods used to evaluate each of the soil samples. Analytical results for soil are included in tabular form in Appendix A. Borehole logs, well completion diagrams, well development records, and survey data are included in Appendix B. Geological data are presented in Section 3 to characterize the physical setting of the site. Analytical results for soil are used in Section 4 to characterize the nature and extent of soil contamination at Area D, and in Section 6 to estimate potential leaching effects on groundwater quality.

2.4 GROUNDWATER SAMPLING

Groundwater samples were collected from new and existing groundwater monitoring wells at Area D to define the nature and extent of dissolved petroleum hydrocarbon contamination. Geochemical data relevant to documenting the potential for biodegradation of dissolved COPCs and quantitatively investigating environmental fate and transport also were collected. Groundwater samples were collected using the procedures described in the work plan (ES, 1994a). These procedures are in accordance with the general procedures outlined in Section 8.5 of *A Compendium of Superfund Field Methods* (EPA, 1987). Investigation activities included well purging and sampling, water level measurements, and field and fixed-base analytical measurements.

Two types of groundwater sampling and analysis was performed at Area D to evaluate natural attenuation processes in accordance with the draft AFCEE document *Technical Protocol for Implementing the Intrinsic Remediation (Natural Attenuation) with Long-Term Monitoring Option for Dissolved Fuel Contamination in Groundwater* (Wiedemeier *et al.*, 1995), prepared by Parsons ES and the EPA's Subsurface Protection and Remediation Division. Thirty-two wells were sampled and analyzed in the field for geochemical parameters relevant to documenting contaminant biodegradation. Twenty of these wells also were sampled for chemical-specific analysis using fixed-base methods. Each of these activities is described briefly in the following sections. All groundwater sampling locations are shown on Figure 2.3. A summary of field and fixed-base analytical analyses performed by sampling location is provided in Table 2.2. Three groundwater monitoring wells (MW-36, MW-37, and MW-38) at the site were not sampled due to slow groundwater recharge and insufficient well groundwater volume.

2.4.1 Field Screening and Analysis

Because the pH, temperature, conductivity and other geochemical parameters of groundwater will change during shipment to a fixed laboratory, field measurements were employed. Field parameter values were determined from "fresh" water samples collected by the same means as those submitted for fixed-base analysis. Samples from existing wells installed by FMG were collected and analyzed in the field by ES personnel in August 1994. All new wells installed by Parsons ES were sampled in late September and early October 1994.

Table 2.1 summarizes the types of field measurements completed at Area D as part of this demonstration. The complete list of field measurements by sample location is presented in Table 2.2. Results of field sampling and screening are used in Section 4 to characterize the nature and extent of groundwater contamination at Area D. Field screening results are also used in Section 6 to assess the potential effects of natural physical, chemical, and biological processes on contaminant concentrations, mass, form, persistence, and mobility. Field results are presented in tabular form in Appendix A.

2.4.2 Analytical Sampling

Groundwater samples were collected at five existing wells and 15 of the newly-installed wells for fixed-base analysis. A product sample was collected from MW-6 by Huntingdon Engineering and Environmental, Inc. at the request of Parsons ES in late December 1994. The complete list of analytical methods used to evaluate groundwater samples by sampling location is presented in Table 2.2. QA/QC samples also were collected and analyzed in accordance with Appendix A of the work plan (ES, 1994a).

Hydrogeological characterization data are presented in Section 3 to characterize the physical setting of the site. Analytical data are used in Section 4 to characterize the nature and extent of groundwater contamination at Area D. Analytical results also are used in Section 6 to assess the potential effects of natural physical, chemical, and biological processes on contaminant concentration, mass, form, persistence, and mobility. All groundwater sampling results are presented in tabular form in Appendix A.

2.5 AQUIFER TESTING

Aquifer slug tests were performed at nine wells in and around Area D to estimate the hydraulic conductivity of the shallow saturated zone. Testing was performed by Parsons ES personnel in early October 1994. Testing locations are shown on Figure 2.4. Rising and falling head tests were performed at each testing well. Water levels during testing were recorded on a Hermit Environmental Data Logger (Model SE1000B). Tests were conducted in accordance with the work plan (ES, 1994a). Aquifer test results are described in Section 3, and test data and analyses are presented in Appendix C.

2.6 SEISMIC REFRACTION SURVEY

A seismic refraction survey was performed adjacent to Area D to assist with delineation of lateral changes in the alluvium/bedrock interface. All geophysical surveying was performed by Parsons ES in early November 1994. A comparison of known bedrock depths to refraction survey data was performed first to confirm the alluvium/bedrock interface could be detected using the seismic refraction technique. Optimum acquisition parameters also were determined from the demonstration. Following positive results from the demonstration, four additional refraction spreads (115 feet in length) were collected. The locations of the spreads are shown on Figure 2.4. Further information on the survey and data analysis is presented in Appendix D. Results of the survey are discussed Section 3.

2.7 SOURCE REDUCTION FEASIBILITY TESTING

Bioventing is an innovative technology that uses low rates of air injection to supply oxygen to soil bacteria employed in the biodegradation of fuel hydrocarbons. A bioventing pilot test was performed at Area D in 1993 and 1994 to assess whether this low-cost source removal technology could be used to remediate contaminated soil if necessary. This pilot test was performed as part of a nationwide AFCEE bioventing initiative to evaluate this type of source removal technology at different types of sites. In August 1993, three vapor monitoring points and two air injection bioventing test wells were drilled and installed at the site. Respiration testing, an air permeability test, and an oxygen influence test were completed in accordance with the procedures described in the AFCEE protocol documents (Hinchee *et al.*, 1992; Downey and Hall, 1994).

In April 1994, 6-month respiration testing was performed at the site to assess system performance. During the field effort in September 1994, final respiration testing was performed, and confirmatory soil gas and soil samples were collected. The initial respiration test results indicated a high oxygen utilization rate. Based on these

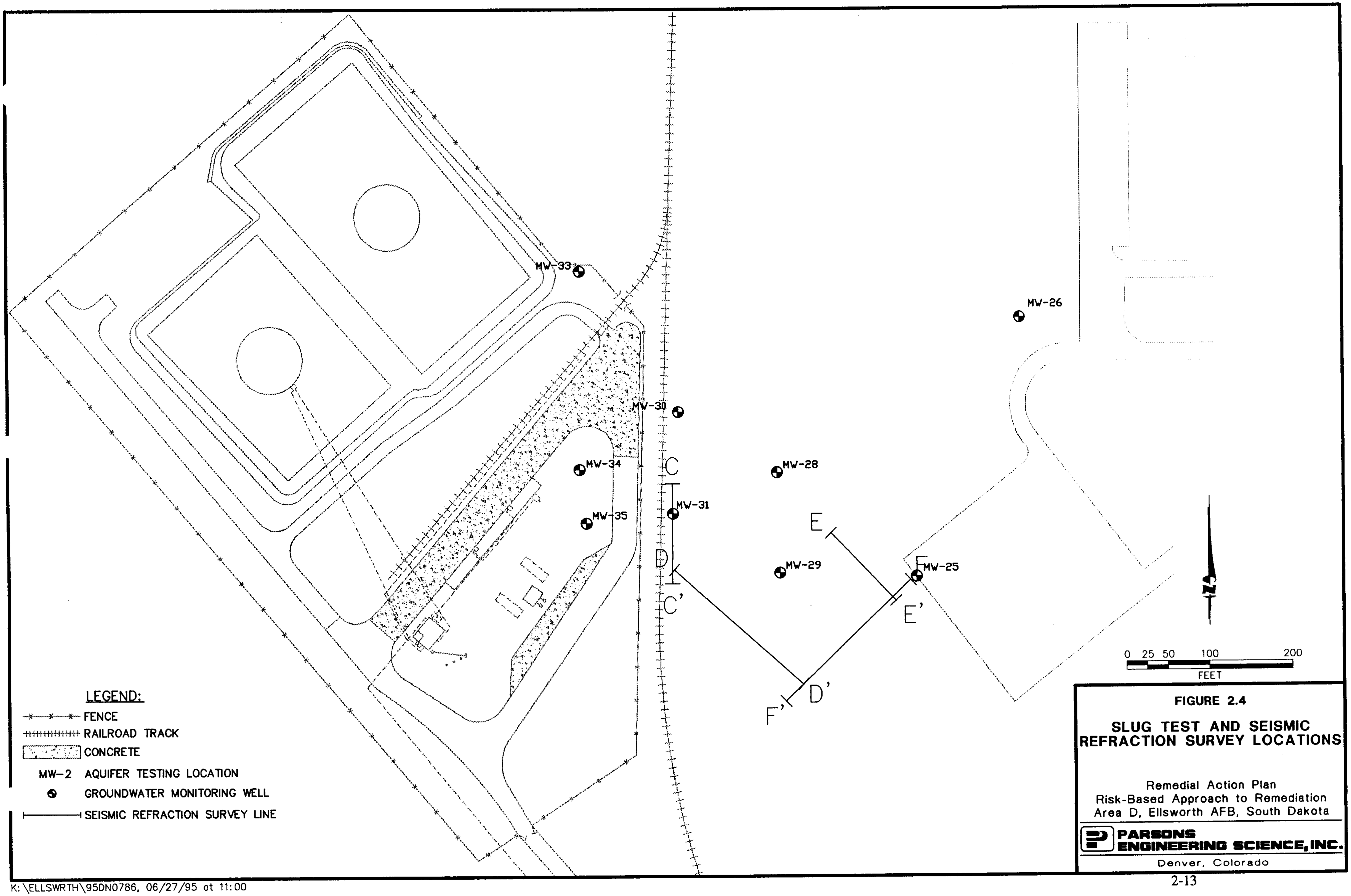

FIGURE 2.4

SLUG TEST AND SEISMIC REFRACTION SURVEY LOCATIONS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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respiration test data, an estimated 1,510 to 2,720 mg of fuel per kg of soil can be degraded each year at this site. One-year confirmatory soil sampling data indicated that BTEX concentrations had appreciably decreased in both soil and soil gas. The treatability testing indicates that *in situ* bioventing is a feasible and cost-effective method of remediating unsaturated hydrocarbon-contaminated soils within the source area at Area D. Data related to the bioventing feasibility test are summarized in Section 7, and demonstration data and analyses are presented in Appendix F.

To assess the feasibility of using either passive or more active product recovery techniques at Area D, a baildown test was performed at MW-6 in October 1995. A baildown test could only be conducted at one monitoring well because it is the only well where LNAPL has been measured in the past year. The baildown test indicated a very slow rate of recovery, indicating that little recoverable LNAPL is present at and within the vicinity of MW-6. Consequently, more active product recovery techniques, such as pump drawdown recovery and bioslurping, may not be a technically feasible or cost-effective method for minimizing residual LNAPL at Area D. These test results are summarized in Section 7, and the baildown test data and analyses are presented in Appendix F.

SECTION 3

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

This section describes the physical characteristics of Area D, as determined from data collected during the 1991/1992 fuel spill survey conducted by FMG and from data collected by ES in August 1993, during the initial bioventing system installation, and in the summer and fall of 1994, as part of the risk-based remediation investigation. Data incorporated into this section from previous investigations were taken from both phases of the fuel spill contamination survey performed by FMG (1991 and 1992). Additional Basewide information was taken from the *Draft Workplan for Operable Unit 11 for Remedial Investigation/Feasibility Study at Ellsworth Air Force Base, Rapid City, South Dakota* (EA, 1994). A summary of all site characterization activities performed by ES/Parsons ES at Area D as part of the risk-based investigation is presented in Section 2 of this RAP.

3.1 REGIONAL TOPOGRAPHY AND SURFACE WATER HYDROLOGY

Ellsworth AFB is located on the Missouri Plateau subdivision of the Great Plains Physiographic Province. The topography of this region is relatively flat upland plateaus set among rolling hills (EA, 1994). The Base is located on an upland plateau that runs north-south and gently slopes toward the southeast (refer to Figure 1.3). Local topographic relief across the Base ranges from 40 to 210 feet with an elevation above mean sea level (msl) of 3,250 feet. The northern boundary of the Base is a steep north-facing escarpment. The southern, eastern, and western areas of the Base consist of the rolling hills typical of the area.

Surface water drainage on the Base generally follows the topographic slope, primarily flowing south to southeast. Seven unnamed ephemeral drainages drain the escarpment at the northern edge of the Base. These drainages flow into Elk Creek, located approximately 5 miles northeast of the Base. The main surface water bodies located on the Base are Bandit, Heritage, Gateway, and Golf Course Lakes. Two unnamed bodies of surface water are located immediately upstream from Bandit Lake. All of these surface water bodies are in the same surface water drainage on the Base Plateau and are connected by an unnamed ephemeral stream which flows primarily south-southeast and eventually discharges into Box Elder Creek, an ephemeral stream 1 mile south of the southern Base boundary.

Area D is in the watershed for this drainage, although it is located approximately 1 mile upgradient from the nearest permanent surface water body. Area D is shown in relation to the on-Base bodies of surface water in Figure 3.1. The drainage and other on-Base ditches and storm sewers eventually discharge into Box Elder Creek. Water

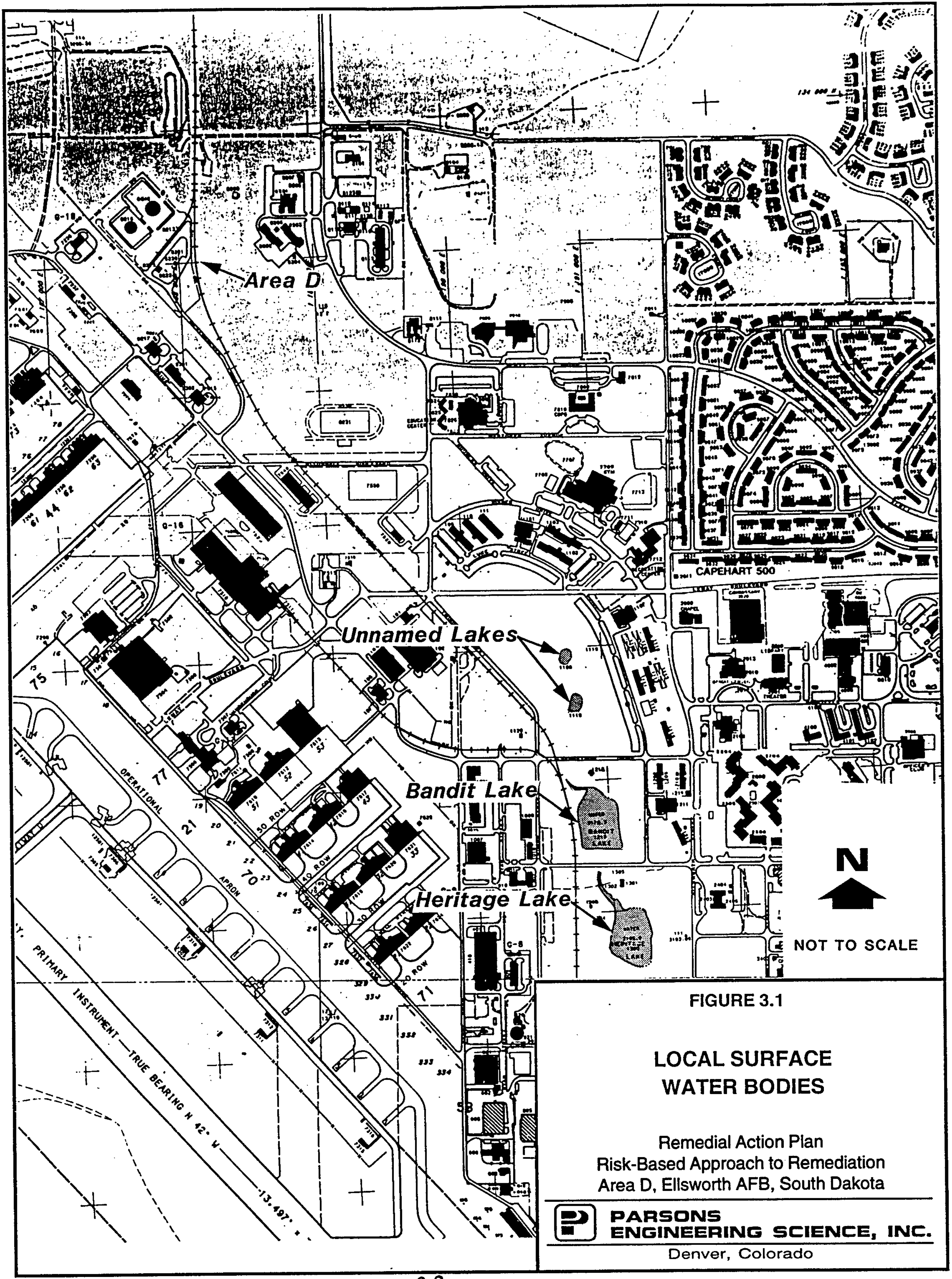

FIGURE 3.1

LOCAL SURFACE WATER BODIES

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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uses designated for Box Elder Creek include irrigation, wildlife propagation, and livestock watering (EA, 1994).

3.2 REGIONAL GEOLOGY AND HYDROGEOLOGY

3.2.1 Geology

Ellsworth AFB lies on the eastern edge of the Black Hills uplift, an elliptical-shaped dome approximately 125 miles long and 45 miles wide. The dome has a north-south trend and resulted from uplifting during the Laramide Orogeny. During this time, the area to the west of the Base was uplifted, and overlying Mesozoic and Paleozoic strata were uplifted, eroded, and deformed. A geologic cross-section of the Base and adjacent environs is shown in Figure 3.2.

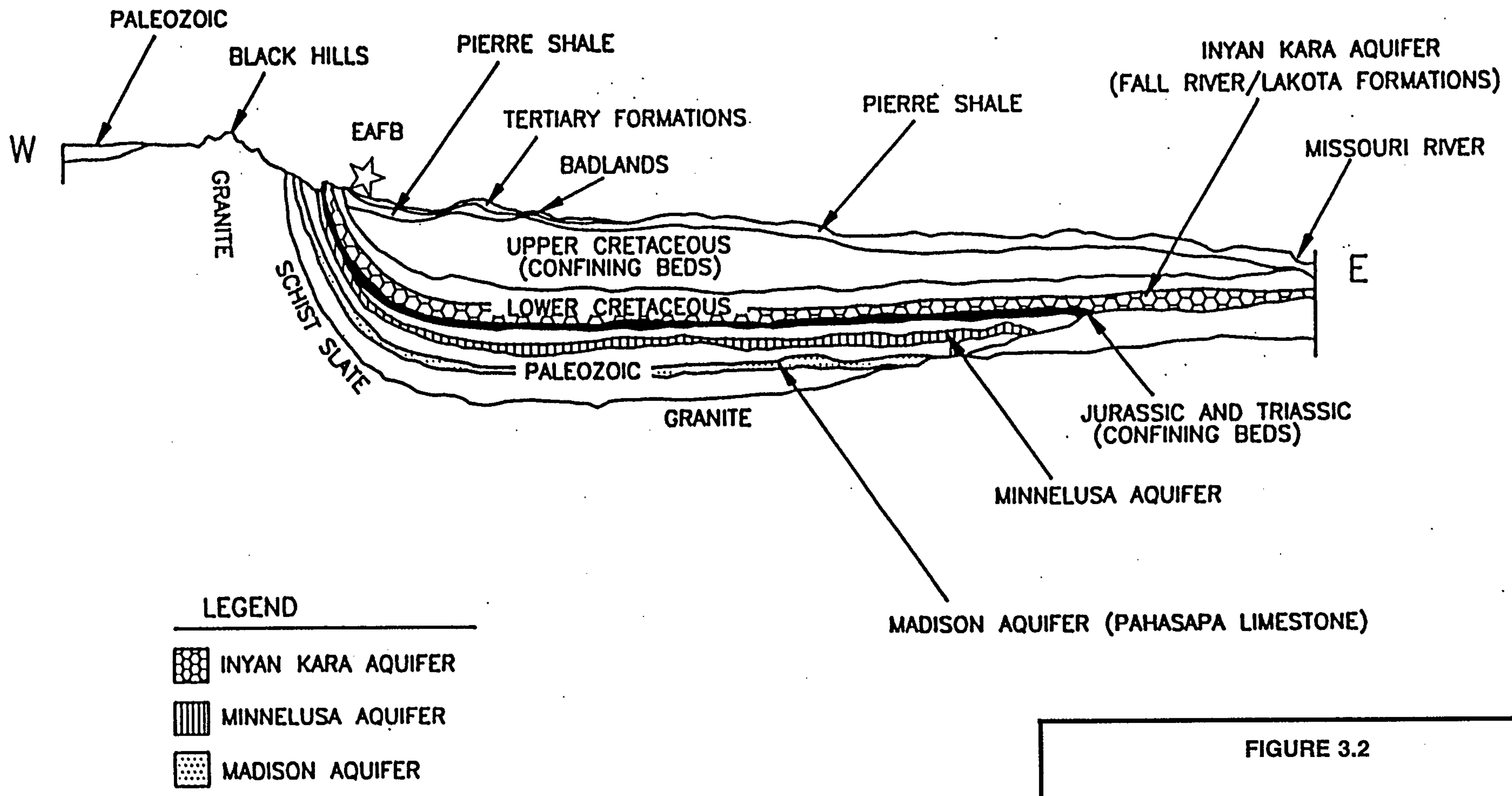
The deepest rocks present below the Base are Precambrian basement rocks overlain by Cambrian- and Jurassic-age deposits of limestone, sandstone, and dolomite. Several of these deposits are known deep aquifers in the area. Overlying the Jurassic deposits is a sequence of Upper Cretaceous-age marine shales with intermittent beds of sandstone and limestone. These marine shales outcrop at various locations throughout Ellsworth AFB and are estimated to be 860 feet thick in the vicinity of the Base. Beds slope gently to the east or southeast in the vicinity of the Base. The shale in the area of the Base is referred to as the Pierre Shale and is characterized as being dark to light gray, blocky, and fractured. The upper weathered zone of the shale is typically highly fractured, with metal oxides filling or coating the fractures.

In the northern portion of the Base, the shale is overlain by a thin veneer of soil, landslide deposits, and gravelly stream deposits. At the southern edge of the Base, thicker gravel deposits associated with Box Elder Creek overlay the shale. Depth to the shale varies across the Base, ranging from surface outcrops to up to 40 feet bgs (EA, 1994).

3.2.2 Hydrogeology

One unconfined and three confined aquifers are known to be present in the vicinity of Ellsworth AFB. The three deeper, confined aquifers are known (in order of increasing depth) as the Inyan Kara, Minnelusa, and Madison aquifers. The unconfined aquifer is found in near-surface alluvial deposits overlying the Pierre Shale (EA, 1994).

The shallow aquifer at Ellsworth AFB is present within the top of the weathered Pierre Shale and overlying deposits of unconsolidated material. Average depth to the groundwater surface ranges from 15 to 30 feet bgs, with a saturated thickness of 10 to 15 feet. The Pierre Shale is considered the confining layer at the bottom of this shallow aquifer. In some locations at the northern edge of the Base, no evidence of a shallow aquifer has been found. Groundwater flow in this shallow aquifer closely follows the shale bedrock topography. Groundwater flows to and along bedrock lows. Groundwater flow rates typically are slow due to the low permeability of the weathered shale. Permeability of the clayey weathered shale has been approximated as 1×10^{-7} to



SOURCE: IRP Stage I Report, USAF, 1989

NOT TO SCALE

FIGURE 3.2

REGIONAL GEOLOGICAL CROSS SECTION

Remedial Action Plan
Risk-Based Approach to Remediation
Area D,Ellsworth AFB, South Dakota

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$1x10^{-8}$ centimeters per second (cm/sec) (EA, 1994). No groundwater is extracted from this hydrogeologic unit on-Base to meet potable or non-potable demands. However, shallow groundwater from this upper, unconfined aquifer is occasionally used to meet domestic and livestock water supplies off-Base (State of South Dakota, 1992; EA, 1994). Current and foreseeable uses of shallow groundwater resources are fully described in Section 3.6.4.

The Inyan Kara aquifer is the shallowest of the confined aquifers. The aquifer lies approximately 1,900 feet bgs and consists of 300 to 500 feet of permeable sandstone bounded by impermeable Upper Cretaceous strata above and Permian-Jurassic strata below. Average yield from the aquifer is 200 gallons per minute (gpm), and flow is assumed to be toward the east-northeast, along the direction of dip of the water-bearing strata. This aquifer is heavily used as a domestic water source for the Rapid City area.

The Minnelusa aquifer is a 600-foot-thick limestone unit approximately 3,460 feet bgs. The water-bearing strata is found between the overlying Permian-Jurassic confining beds and underlying Pennsylvanian beds. Average yield from this aquifer is 150 gpm. Flow in the aquifer is assumed to be toward the east-northeast in the direction of dip of the water-bearing strata and confining beds. The uppermost part of the Minnelusa aquifer is the most heavily used groundwater source in the communities surrounding the Base.

The Madison aquifer is the deepest aquifer in the vicinity of the Base. The water-bearing stratum is a bed of limestone that is about 350 thick beginning at 4,150 feet bgs. The aquifer is located below the Lower Pennsylvanian confining strata. As with the other confined aquifers in the area, flow is assumed to be to the east-northeast. Yield from this aquifer ranges from 22 to 500 gpm. This aquifer is not currently used as a water source due to its depth and the associated costs of drilling and pumping (EA, 1994).

3.3 SITE TOPOGRAPHY AND SURFACE WATER HYDROLOGY

Area D and the surrounding area generally slopes to the east. The slope is most pronounced in the area immediately east of the fuel yard entrance road. The area to the east of the site is general level (refer to Figure 1.4). The average surface elevation of the site is 3,250 feet msl. The Soil Conservation Service (SCS) has identified one primary soil association at Area D, clay loam soils of the Nunn clay association. The permeability of these soils can range from less than 4.2×10^{-5} to 4.2×10^{-3} cm/sec (EA, 1994).

Surface features at the site include grassy areas; concrete, asphalt, and gravel driveways and parking areas; and two buildings (Figure 1.4). Building 8215 is the transfer and unloading pumphouse that controls flow of JP-4 jet fuel in the POL yard. Building 8220 is a smaller building that houses pumps for the gasoline and diesel fuel USTs located at the site. Underground fuel pipelines, some of which may have leaked previously, are the suspected source of contamination at this site.

There are no surface water bodies located in the immediate vicinity of Area D. The nearest permanent surface water features are located approximately 1 mile southeast of the site. Surface drainage at Area D is primarily toward the south, paralleling the concrete and asphalt roads in the fuel yard. A storm water drain is located just south of Building 8215 along the concrete roadway.

3.4 SITE GEOLOGY AND HYDROGEOLOGY

The vadose zone and shallow aquifer system at Area D were characterized by ES personnel from August through October 1994. Data collected as part of this demonstration were used to supplement geologic and hydrogeologic data collected during the fuel spill survey (FMG, 1991 and 1992).

3.4.1 Site Lithology and Stratigraphic Relationships

Drilling and soil sampling results at Area D show that the local geology consists of a veneer of unconsolidated alluvial and colluvial material overlying the Pierre Shale. The unconsolidated material consists of Quaternary and Recent alluvial deposits of sand, gravel, silt, and clay. Generally, the stratigraphy of the deposits can be described as 8 to 25 feet of lean clay and silt, overlying 2 to 11 feet of coarse gravel and cobbles that rests on weathered Pierre Shale. The shale was encountered at 14 to 28 feet bgs at the site. No soil boreholes were completed more than 10 feet into the Pierre Shale as part of this investigation. Based on previous investigations, the shale is estimated to be 860 feet thick. The shale is considered to be the bottom (confining layer) of the shallow, unconfined aquifer at Area D.

During the course of drilling for the site investigation it became apparent that a paleochannel runs northward from the center of Area D. This channel can be seen in Figure 3.3, a bedrock contour map of Area D, and in cross section A-A' (Figure 3.4). The channel appears to travel under the fuel yard and the railroad tracks, and run into a large bowl-shaped depression beneath the field adjacent to the site. To confirm the existence of this depression, a geophysical seismic refraction survey was performed along the lines shown in Figure 3.3. A general dip was observed from the outside edge of the field toward its center. This dip can be seen in the vicinity of MW-29 on Figure 3.5, an east-west hydrogeologic cross-section of the site. The results of the geophysical seismic refraction survey confirmed the results of the bedrock contour map developed from drilling borehole logs. No evidence of further channeling out of the depression was detected during either drilling activities or the seismic survey. A complete discussion of the geophysical survey is provided in Appendix D.

3.4.2 Site Hydrogeology

The groundwater table depth at Area D at the time of well installation ranged from 13 to 28 feet bgs. Groundwater elevation data collected on November 8, 1994, were used to construct the groundwater contour map shown in Figure 3.6. These data indicate that groundwater appears to be following bedrock contours as it flows through the site. These data support the hypothesis that the Pierre Shale is the bottom confining layer of the shallow aquifer; groundwater is flowing into and along bedrock lows and

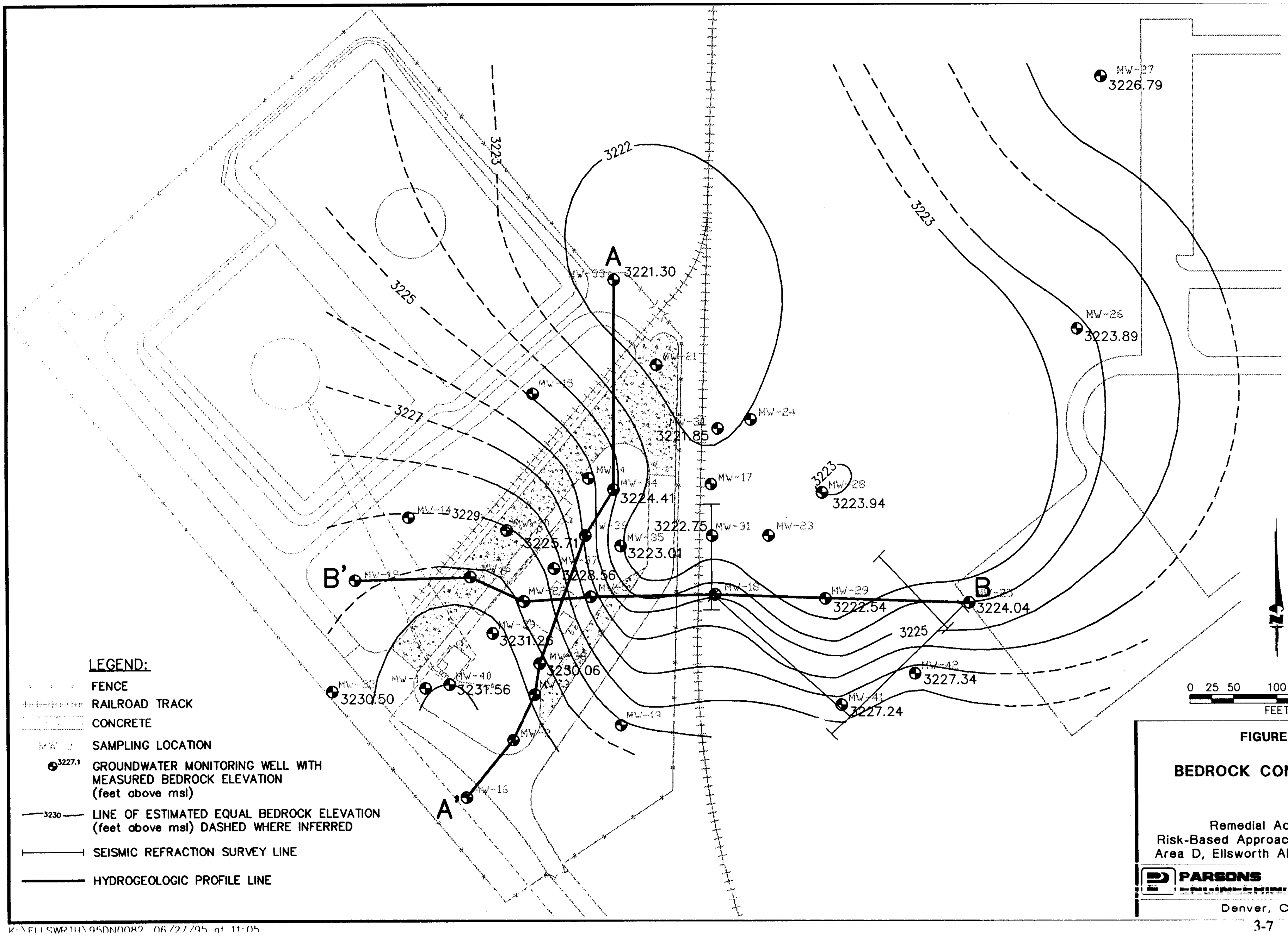

FIGURE 3.3

BEDROCK CONTOUR MAP

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Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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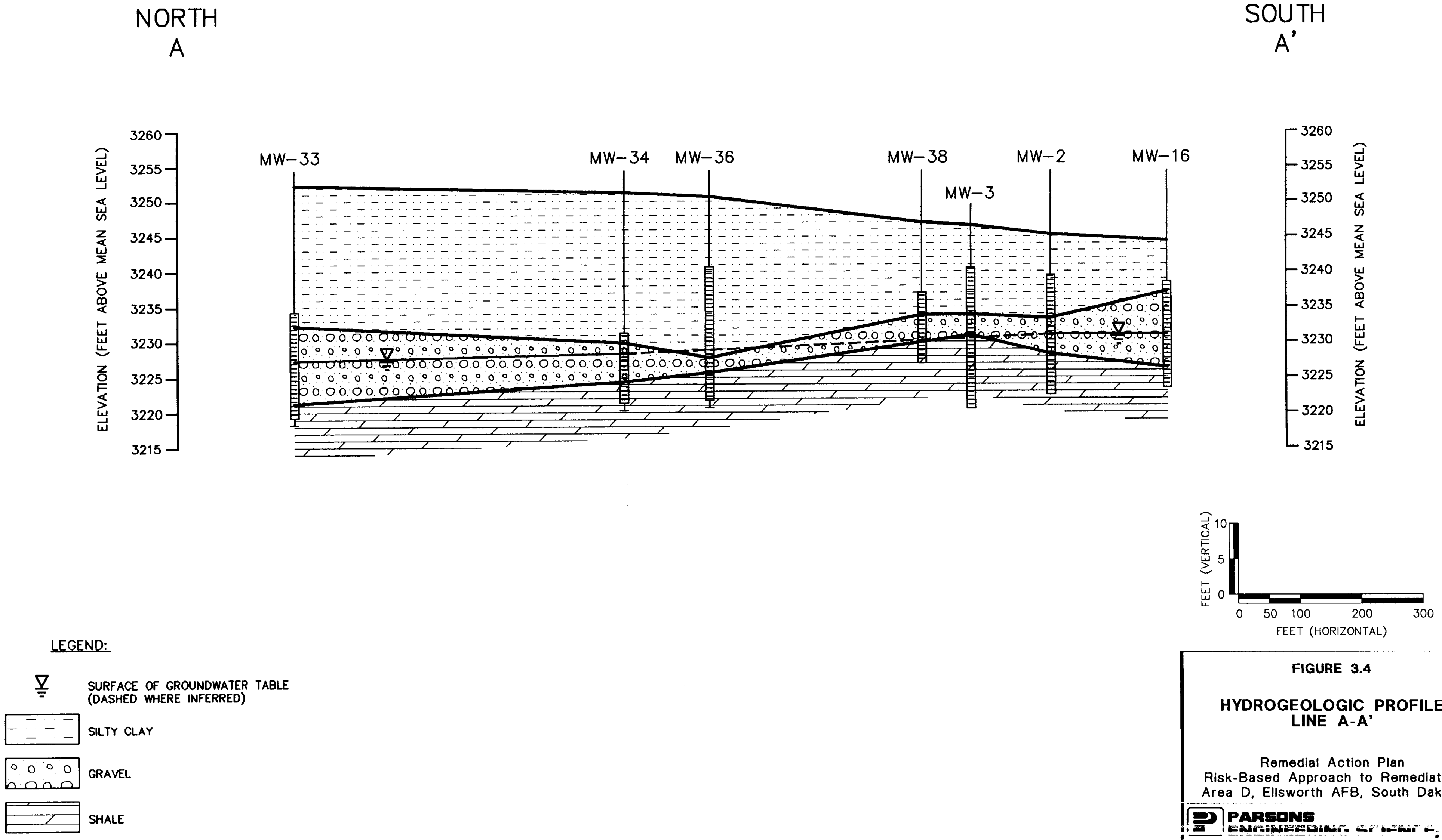

FIGURE 3.4

**HYDROGEOLOGIC PROFILE
LINE A-A'**

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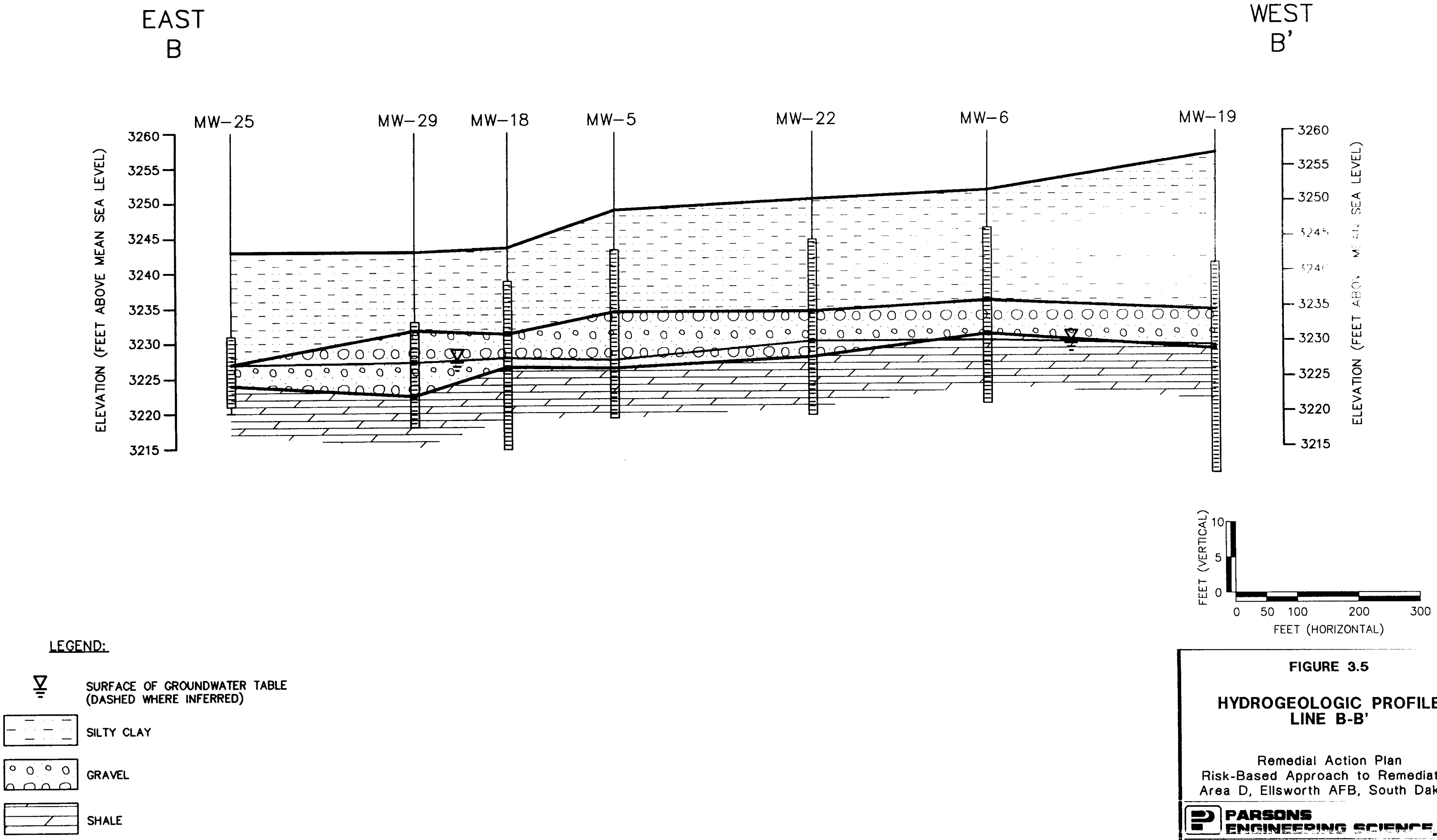

FIGURE 3.5

HYDROGEOLOGIC PROFILE LINE B-B'

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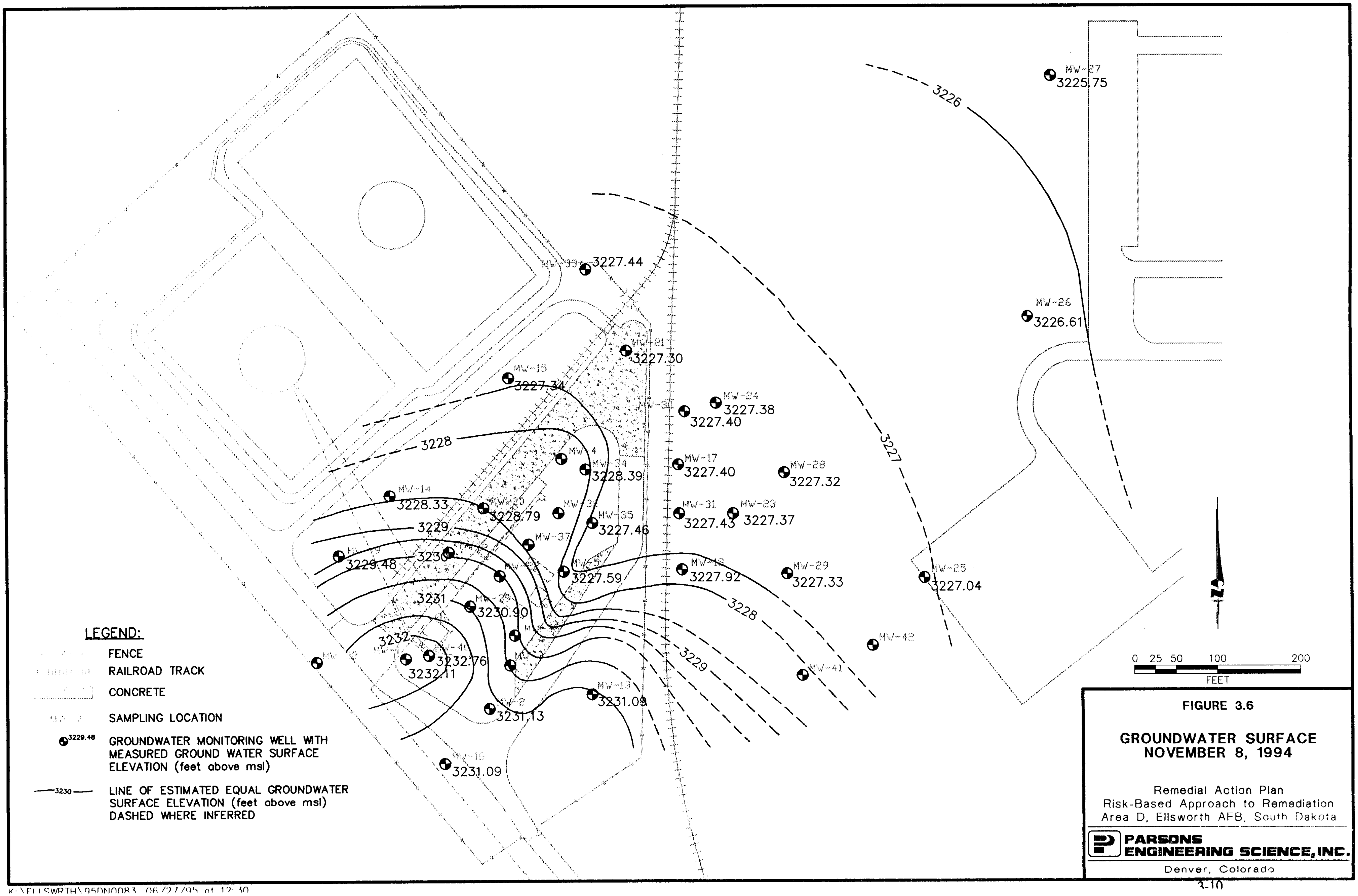

LEGEND:

FENCE

RAILROAD TRACK

CONCRETE

SAMPLING LOCATION

3229.48 GROUNDWATER MONITORING WELL WITH MEASURED GROUND WATER SURFACE ELEVATION (feet above msl)

3230 LINE OF ESTIMATED EQUAL GROUNDWATER SURFACE ELEVATION (feet above msl) DASHED WHERE INFERRED

FIGURE 3.6

GROUNDWATER SURFACE
NOVEMBER 8, 1994

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channels. The hydraulic gradient varies widely across the site. Gradients are very steep in the vicinity of the paleochannel and very shallow in the area of the bedrock depression east of the fuel yard boundary.

Based on slug tests performed at nine well in and around Area D, the hydraulic conductivity varies from 0.7 to 7 feet per day (ft/day). A complete discussion of aquifer slug testing at the site is presented in Appendix C. The wide range of hydraulic conductivity values measured at the site can be attributed to differing saturated thicknesses. In areas having a large saturated thickness, groundwater flows readily through the unconsolidated gravel layer resting on the shale. In areas where the saturated interval is very thin, groundwater flow is restricted primarily to the less-permeable weathered shale at the very bottom of the shallow aquifer.

A maximum linear advective groundwater velocity was calculated to be approximately 0.4 ft/day. This was based on a maximum hydraulic gradient of 0.017 foot per foot (ft/ft) in the vicinity of the paleochannel, the maximum hydraulic conductivity value of 7 ft/day, and an assumed porosity of 0.30.

3.5 CLIMATOLOGICAL CHARACTERISTICS

Ellsworth AFB is located in a semi-arid area that is characterized by warm, dry summers and cold winters. Mean monthly temperatures range from 23 degrees Fahrenheit (°F) in January to 74°F in July. The maximum recorded temperature from 1981 to 1991 was 111°F, and the minimum was -29°F. Average annual precipitation for the period of 1951 to 1980 was 18.4 inches. The net annual precipitation has been calculated to be negative 24 inches. This value was calculated by subtracting total evapotranspiration from total annual precipitation (EA, 1994). The highest mean monthly precipitation of 3.02 inches occurs in June, and the lowest, 0.42 inches, occurs in December. Mean snowfall ranges from 8.9 inches in March to 0 inch in July and August. The prevailing wind direction is from the north-northwest except during the month of the July, when wind direction usually shifts 180 degrees to originate from the south-southwest. Average wind speed ranges from 7 to 9 knots [8 to 10 miles per hour (mph)]. The maximum recorded windspeed during the period from 1981 to 1991 was 78 knots (90 mph).

3.6 LAND USE

3.6.1 Site Access

Area D is located near the center of the Base in a controlled-access area. The site can be accessed only by first passing through one of the manned guard gates at the perimeter of the Base, and then contacting Fuels Supply to have the gate to Area D unlocked. Personnel in the fuel yard must be accompanied by a member of the Fuels Supply Squadron at all times. The field adjacent to the site is not a controlled area and is accessible to anyone on the Base. The entire Base is surrounded by a barbed wire or chain-link fence. Main access to the Base is through the main gate located off of Ellsworth AFB Access Road. The guard station at the main gate is manned 24 hours per day, 7 days per week.

3.6.2 Current Land Use

Ellsworth AFB is located on the border of Pennington and Meade Counties, about 4,800 feet north of the Box Elder Corporate limits (EA, 1994). The Base is an active military installation with an airfield, hangers, maintenance and administrative buildings, and residential and recreational facilities. Property to the north and west of the Base is used as open range/farm land. Parcels of land south of the Base are used as farmsteads, acreages, and small residential developments. The town of Box Elder is located along the banks of Box Elder Creek approximately 0.5 mile south of the Base. Property east of the Base is zoned and used as residential and commercial land. The area of residential development extends north along the eastern edge of the Base to the school gate. Box Elder and its associated housing areas is the only area of concentrated population adjacent to the Base.

Area D is currently an active fuel supply yard (i.e., used as an active military flight operations support area). The field east of the fuel yard is currently vacant and covered with native vegetation. The fuel yard and adjacent field are surrounded by open fields, industrial-use buildings, and office buildings. An open field is present directly north of the site. Beyond this field is a small industrial area. A sports field and running track is located at the far southern edge of the field. A rifle range is located approximately 0.25 mile northeast of the site. Base Civil Engineering and the local US Army Corps of Engineers (USACE) offices are located 600 feet east of the site and the adjacent field. The North Dock area of the airfield is located west and southwest of the fuel yard. All buildings in the vicinity of the site typically are occupied only during normal working hours. Buildings within Area D are occupied only during fueling activities at the site. There are no military or civilian residential areas within 1 mile of the site.

3.6.3 Proposed Future Land Use

No change in the use of this site has been proposed. The Base is active and has not been included on any of the Department of Defense Base Closure and Realignment Commission's lists for military base closures. Area D is the main fuel distribution facility for all aircraft at the Base and is not expected to be removed from service any time in the foreseeable future. If the Base is identified for closure in the future, proposed land use at the site should be re-evaluated accordingly.

3.6.4 Groundwater Use

There are no current uses of shallow groundwater from the unconfined aquifer on-Base (EA, 1994). Ellsworth AFB currently obtains its potable water supply from the Rapid City Water Service. One of the major sources of domestic water in the Rapid City area is the deeper Inyan Kara aquifer, although the groundwater extracted from the even deeper Minnelusa aquifer and surface water collected and stored at Pactola Reservoir represent the largest and most dependable sources of potable water in the area. These water supplies are considered to be sufficient to meet at least a 10-percent increase in the served population in the region (Rapid City Water Service, 1994).

However, shallow groundwater from the upper unconfined aquifer is occasionally used to meet domestic and livestock water supplies off-Base (State of South Dakota, 1992; EA, 1994). There are about 45 known, shallow wells or infiltration galleries used to extract groundwater for domestic applications at sites near the Base. These shallow groundwater wells range in depth from about 30 to 60 feet bgs. The nearest well used to meet potable demands is more than 2 miles downgradient from Area D. Widespread use of the shallow groundwater as a major source of potable water is not expected because both the yield and water quality from the alluvial aquifer is highly variable, apparently depending on the saturated thickness of the unconfined aquifer in the immediate area. Low water yield is observed when groundwater flows through the thin, less permeable deeper portions of the alluvial aquifer. Yield rates in unconsolidated gravel layers of the unconfined aquifer range from less than 1 gpm to several hundred gpm. Yield rates from thinner aquifer material just above and within the Pierre Shale may be about 1 to 5 gpm in large-diameter wells (EA, 1994). These materials are apparently too dense and nonporous to yield significant volumes of water. Three of the new groundwater monitoring wells installed into the upper 2 feet of the Pierre Shale at Area D in September 1994 contained no measurable volume of water as of mid-November 1994.

Elevated concentrations of total dissolved solids (TDS) also apparently correspond to a thin saturated interval. The range of TDS measured in groundwater samples collected at Area D as part of the risk-based investigation ranged from 153 to more than 2,300 milligrams per liter (mg/L). Generally, groundwater in the shallow aquifer is a sodium-sulfate type water that can contain elevated concentrations of selenium and other minerals (Stach *et al.*, 1990). If sufficiently elevated, the TDS content and/or natural concentrations of metals such as selenium can render the water unfit for human consumption.

SECTION 4

NATURE AND EXTENT OF CONTAMINATION

4.1 OVERVIEW

This section summarizes the nature and extent of soil and groundwater contamination at Area D based on the findings of site characterization activities conducted under the two phases of the fuel spill contamination survey conducted in 1991 and 1992, the bioventing pilot test conducted at the site in 1993 and 1994, and the risk-based remediation site investigation conducted in 1994 and 1995. Data collected under the 1991/1992 fuel spill survey and the 1993 initial pilot bioventing test were used to describe the historical nature and extent of soil and groundwater contamination at the site. Data collected during the 1994 pilot bioventing test and the 1994/1995 risk-based site investigation were used to delineate the current nature and extent of site-related contamination.

As described in the work plan (ES, 1994a), conservative contaminant screening criteria for soil and groundwater are used initially to define the nature and extent of contamination in soil and groundwater pursuant to evaluating remedial requirements to protect human health and the environment. The conservative contaminant screening levels, or "trigger levels", used in this evaluation were defined by EPA (1994) for soils, and are either equal to or less than the most conservative promulgated standard for groundwater. The conservative contaminant screening criteria used to identify media warranting more in-depth consideration are explained more fully in Section 4.3.

4.2 SOURCES OF CONTAMINATION

Contamination at Area D was the result of a leaking UST or fuel transfer line discovered during a 1990 system pressure test. SDDENR was notified of a potential subsurface leak at Area D on September 11, 1990. An unknown amount of fuel was released into the subsurface from an unknown point in the fuel system at Area D. It is suspected that the chemical source of contamination at the site is JP-4 jet fuel because it is the primary fuel stored at Area D. Additionally, the greatest contamination in both groundwater and soil at the site was found adjacent to fuel lines that are used for the transport of JP-4 jet fuel. The fuel spill survey (FMG, 1991 and 1992) and the 1993 sampling results collected under the initial pilot bioventing test (ES, 1993a) conducted at Area D indicated that soil and groundwater had elevated concentrations of the BTEX compounds.

Residual LNAPL was reported during drilling of BH-10 and installation of MW-4 in 1991 (FMG, 1991). However, no free LNAPL was found in MW-4 after the well was developed, and BH-10 was not completed as a well. FMG (1992) reported variable levels of LNAPL in MW-6 during the second phase of the fuel spill survey. Although three permanent wells were installed adjacent to MW-6 immediately after discovery of this LNAPL to delineate the probable extent of LNAPL at the site (i.e., MW-19, MW-20, and MW-22), no LNAPL has ever been encountered at these sampling locations. The presence of LNAPL in MW-6 is most likely the result of a subsurface leak in adjacent JP-4 transfer lines.

The 1994 risk-based investigation provided more recent information on the nature and extent of LNAPL at the site. Because MW-4 had collapsed and was filled with silt and sand, it was not possible to ascertain if residual or mobile LNAPL is present at this sampling location. LNAPL was encountered at the site only in MW-6 during both the 1994 sampling event and the 1995 baildown test. The physical behavior and chemical nature of this LNAPL in 1994 suggests that either a new release of JP-4 to the subsurface may have occurred, or that a continuous leak may be present. No LNAPL was encountered in MW-6 when it was first prepared for sampling in August 1994. The well was bailed dry at that time, and no water was measured in MW-6 for more than a week following initial well evacuation. In early November 1994, approximately 6 inches of LNAPL was measured in MW-6. However, the total liquid level measured in the well (including product) was 5.5 feet below the initial water level measured in August 1994 before the well had been bailed dry. The well had not fully recharged to its static water level in more than 70 days. A sample of LNAPL was collected from MW-6 in later 1994, and submitted for chemical analysis. Table 4.1 compares analytical data for specific compounds in the product collected at MW-6 to the range of concentrations of the same compounds typically found in fresh JP-4 jet fuel. The strong similarities between these two data sets suggests that the product collected in MW-6 is not weathered significantly. This was not expected because the release that was initially suspected to have caused soil and groundwater contamination at the site occurred in 1990. The lack of weathering of the product in MW-6 is a strong indicator of a more recent or ongoing release of fresh JP-4 jet fuel into the subsurface. Ellsworth AFB personnel were notified of this finding. Additional pressure testing for the USTs and transfer lines at Area D (which was completed by Ellsworth AFB) suggested that no large system leak still exists at the site. Several leak detection wells have been installed to monitor for any additional leaks.

Approximately 1.5 feet of LNAPL thickness was encountered at MW-6 on October 12, 1995, before initiating the baildown test. Once all recoverable fluids had been bailed from MW-6, the LNAPL thickness never rose above 2 inches after a 48-hour observation period. These data suggest that little recoverable free product exists in the vicinity of MW-6. Additionally, no measurable LNAPL thickness was found in any of the monitoring wells or leak detection wells within a 80-feet radius of MW-6 during this baildown test. The absence of LNAPL in adjacent wells and the slow rate of product recovery in MW-6 both imply that no significant LNAPL plume likely exists at the site. However, the isolated pocket of LNAPL may continue to act as a source of contaminant mass to groundwater over time.

TABLE 4.1
CHEMICAL ANALYSIS OF LNAPL SAMPLE
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Compounds	Reported Concentration in LNAPL from MW-6 (12/94) (µg/L)	Range of Concentration in "Fresh" JP-4 Jet Fuel[a] (µg/L)
Benzene	520,000	82,500 - 3,750,000
Toluene	350,000	219,450 - 9,975,000
Ethylbenzene	2,200,000	611,000 - 2,775,000
Total xylenes	19,000,000	379,500 - 17,400,000

[a] Aurthur D. Little, 1985; Martel, 1987; ES, 1994b.

4.3 CHEMICALS OF POTENTIAL CONCERN

It is the intention of the Air Force to obtain approval for a remedial action for Area D that will protect human health and the environment from exposure to site-related chemicals, the potential human and ecological receptors based on the current and future uses of the site. To accomplish this objective, the specific chemical constituents or COPCs that may drive potential risks and impact the final remedial requirements at Area D were identified. Previous site investigations (FMG, 1991 and 1992; ES, 1993a) and the work plan (ES, 1994a) preliminarily identified COPCs for Area D as the BTEX compounds and possibly naphthalene. These specific chemical constituents were initially defined as COPCs based on existing site characterization data, the chemical nature of the suspected source (i.e., a JP-4 jet fuel), and the analytical requirements specified by the SDDENR for petroleum-contaminated soils and groundwater (Chapters 74:03:32 and 74:03:15).

4.3.1 Contaminant Screening Criteria

Conservative contaminant screening criteria for each of the BTEX compounds and naphthalene for soils and groundwater were developed based on a combination of risk-based and promulgated target cleanup levels. Risk-based contaminant screening levels were developed for each of the BTEX compounds and naphthalene in soil based on recent EPA (1994) soil screening guidance. EPA has calculated generic soil contaminant screening levels for more than 100 individual chemicals that will be protective of human health under the most conservative exposure scenario (i.e., unlimited or residential land use). These generic screening levels were developed to quickly identify soils that may warrant further study and, possibly, remedial action to protect human health and the environment (EPA, 1994a).

Generic contaminant screening criteria developed by EPA (1994) for soils were used as part of this initial screening step for Area D. Three types of potential exposure routes were used to identify soil contaminant screening criteria: incidental soil ingestion, inhalation of VOCs and fugitive dust, and ingestion of groundwater impacted by chemicals leaching from soils. The generic contaminant screening concentrations for carcinogens were calculated to be the concentrations representing an increased cancer risk of one in one million (i.e., 10^{-6} risk level). Benzene is the only chemical potentially present in site soils that may be defined as a carcinogen (Appendix G). Generic risk-based contaminant concentrations for noncarcinogens were calculated to represent no adverse effects on humans (i.e., a hazard quotient of ≤ 1). Toluene, ethylbenzene, and total xylenes have been identified as potential human noncarcinogens, but are not carcinogens (Appendix G).

The most conservative (i.e., stringent) of the three exposure-route, risk-based criteria for each of the BTEX compounds was used as the site-specific contaminant screening level for Area D. Appendix G presents the derivation of these soil contaminant screening criteria in detail. Application of these standardized equations to define soil COPCs is conservative at this site, because Area D is not currently or planned to be available for unlimited use. However, these criteria were used as a simple method to identify the full spectrum of soil COPCs that could be considered when defining remedial requirements for the site to protect human health and the environment. If measured soil concentrations did not exceed these conservative screening criteria, the chemical was not identified as a COPC. If measured soil concentrations exceeded these site-specific screening levels, the chemical was identified as a COPC and considered in subsequent analysis included this RAP. Table 4.2 compares each of the exposure-route risk-based soil contaminant screening criteria for the BTEX compounds to the range of soil concentrations of these compounds measured at the site.

Contaminant screening criteria for groundwater were based on a combination of both promulgated standards and risk-based criteria. Although the SDDENR has not promulgated target soil concentrations for the BTEX compounds or naphthalene (Chapter 74:03:32), chemical-specific groundwater quality standards have been defined (Chapter 74:03:15). Risk-based contaminant screening criteria for groundwater were developed similarly to generic soil criteria, except the only exposure pathway incorporated into the derivation of the target levels was ingestion of contaminated groundwater (Appendix G). Table 4.2 presents both the SDDENR promulgated groundwater quality standards and the risk-based groundwater contaminant screening levels that were calculated to be protective of human health under the most conservative exposure scenario. These screening criteria are compared to the range of data developed from groundwater sampling events conducted in 1991/1992 and 1994. A specific compound was identified as a groundwater COPC if any measured concentration at the site was equal to or exceeded the most stringent of these two potential contaminant screening criteria.

All nondetect analytical results obtained during the 1991/1992 fuel spill survey and the 1994 risk-based remediation investigation are reported on Table 4.2 at the PQL with a "U" data qualifier. This is consistent with EPA (1989) guidance on how to use non-detect values in quantitative risk assessments. All analytical results measured above the MDL but below the PQL were identified as estimated but useable data (J qualified). All MDLs achieved for the 1994 investigation are consistent with the SDDENR recommendations for analytical sensitivity, and are below the most stringent contaminant screening criteria (see Table 2.1). All analytical results measured above the PQL were identified as detected concentrations and not qualified.

Data collected as part of the 1994 risk-based remediation investigation also were subjected to a usability/acceptability review that included (1) a review of chain-of-custody records, reported holding times, status of instrument calibration, and reported recoveries for laboratory control samples and matrix spike/matrix spike duplicates; (2) analyzing and using laboratory and field blanks to qualify reported sample concentrations; and (3) measuring the reproducibility of sampling techniques and laboratory analytical precision using blind field duplicates/replicates. Appendix A presents the analytical results for all samples collected under this project, organized by environmental medium, and a summary of the data evaluation methodology and results.

TABLE 4.2
IDENTIFICATION OF SOIL AND GROUNDWATER CONTAMINANT SCREENING CRITERIA EXCEEDANCES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Compound (units)	1991/1992 Fuel Spill Survey		1993 Initial Bioventing Results		1994 1-Year Bioventing Results		1994 Risk-Based Remediation		Risk-Based Criteria			SDDENR Promulgated Standard
	Minimum Concentration	Maximum Concentration	Minimum Concentration	Maximum Concentration	Minimum Concentration	Maximum Concentration	Minimum Concentration	Maximum Concentration	Ingestion[a/]	Inhalation[b/]	Leaching[c/]	
Soil												
Benzene (mg/kg)	0.2 U	0.4	3.2	15	0.058 U	0.19	0.00043 U	1.1	22	0.5	0.02	--[d/]
Toluene (mg/kg)	0.2 U	17	3.7	13	0.058 U	0.063 U	0.004 J	4.1	16,000	520	5	--
Ethylbenzene (mg/kg)	0.2 U	15	17	53	0.063 U	3.7	0.008 J	2	7,800	260	5	--
Total xylenes (mg/kg)	0.2 U	81	57	310	0.57	21	0.0023 J	74	1.60E+05	320	74	--
Groundwater												
Benzene (µg/L)	0.5 U	2,675	--	--	--	--	0.4 U	3,400	1.2	--	--	5
Toluene (µg/L)	0.5 U	15	--	--	--	--	4 U	35 J	1,400	--	--	1,000
Ethylbenzene (µg/L)	0.5 U	659	--	--	--	--	4 U	640	700	--	--	700
Total xylenes (µg/L)	1 U	1,680	--	--	--	--	4 U	2,700	14,000	--	--	10,000
Naphthalene (µg/L)	--	--	--	--	--	--	10 U	300	280	--	--	10[e/]

NOTE: Shading indicates concentration exceeds the most stringent contaminant screening criterion. Both concentration and exceeded criterion are shaded.

[a/] Risk-based screening criteria calculated to protect against health risks associated with incidental ingestion of contaminated soils or ingestion of contaminated groundwater under unlimited land use scenario.

[b/] Risk-based screening criteria calculated to protect against health risks associated with inhalation of volatiles and fugitive dusts under unlimited land use.

[c/] Risk-based screening criteria calculated to protect against health risks associated with ingestion of groundwater affected by chemicals leaching from soils (unlimited land use scenario).

[d/] Not available.

[e/] Promulgated groundwater quality standard set equal to the project-specific MDL. No federal MCL has been identified.

4.3.2 Identifying Screening Criteria Exceedances

Table 4.3 lists the specific chemicals that were measured in 1991/1992, 1993, or 1994 at concentrations that exceeded any of the contaminant screening criteria for soil and groundwater. Based on these exceedances, the COPCs for soil at Area D are all of the BTEX compounds. The COPCs for groundwater are benzene and naphthalene. Benzene and total xylenes are included as soil COPCs based on 1994 data. Toluene and ethylbenzene are identified as soil COPCs based on 1991/1992 and 1993 analytical results. Benzene was identified as a groundwater COPC in 1991/1992 and 1994 sampling data. However, naphthalene has been identified as a groundwater COPC based on 1994 data only, because it was not a target analytical compound in the 1991/1992 fuel spill survey.

These compounds are considered in detail in subsequent sections. Compounds measured at the site at concentrations that did not exceed these conservative screening criteria have not been carried forward in this analysis. Emphasis has been given to defining the nature and extent of contamination that must be addressed to protect human health and the environment. Only compounds that may pose a health threat (i.e., a carcinogenic and/or noncarcinogenic risk) to potential human receptors, or are relevant to conducting remedial technology assessments, have been considered as part of this risk-based approach to remediation. For example, although total petroleum hydrocarbon (TPH) contamination may be useful as a gross indicator of JP-4 fuel contamination, toxicity data of adequate quality for use in a risk-based assessment are not available.

4.4 SOIL CHEMISTRY

The following sections summarize analytical data results for COPCs measured in soil samples collected during the 1991/1992 fuel spill survey, installation of the pilot bioventing system in August 1993, 1-year bioventing system test conducted in 1994, and the 1994 risk-based remediation investigation.

4.4.1 BTEX Soil Contamination

Soil data were collected during two discrete sampling events conducted under the fuel spill contamination survey at the site (FMG, 1991 and 1992). Twenty-four soil samples were collected from 24 separate sampling locations at various depths in both 1991 and 1992. Concentrations of individual BTEX compounds were detected in only 9 of the 24 soil samples submitted for chemical analysis. The maximum concentration of total BTEX in soil measured at the site in 1991/1992 was 98.4 mg/kg at BH-7, which is located just northeast of Building 8215 (Figure 4.1). The 1991/1992 maximum benzene concentration of 0.4 mg/kg also was measured at this sampling location. Total xylenes generally accounted for more than 70 percent of the total BTEX in contaminated soil samples collected in 1991 or 1992. Table 4.4 summarizes the analytical results for total BTEX measured in soil samples collected at the site under the 1991/1992 fuel spill survey. Figure 4.1 shows the areal extent of total BTEX in soil based on all soil data collected at the site to date.

TABLE 4.3
LIST OF CHEMICALS OF POTENTIAL CONCERN
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Chemicals of Potential Concern	Rationale [a]
Soil	
Benzene	1991/1992 maximum, 1993 minimum and maximum, 1994 bioventing maximum, 1994 risk-based maximum concentration > risk-based leaching criterion
Toluene	1991/1992 maximum, 1993 maximum concentration > risk-based leaching screening criterion
Ethylbenzene	1991/1992 maximum, 1993 minimum and maximum concentration > risk-based leaching screening criterion
Total xylenes	1991/1992 maximum, 1993 maximum, 1994 risk-based maximum concentration > risk-based leaching screening criterion
Groundwater	
Benzene	1991/1992 maximum, 1994 risk-based maximum concentration > risk-based screening criterion and promulgated standard
Naphthalene	1994 risk-based maximum concentration > risk-based screening criterion and project-specific MDL

[a] See data ranges presented in Table 4.2.

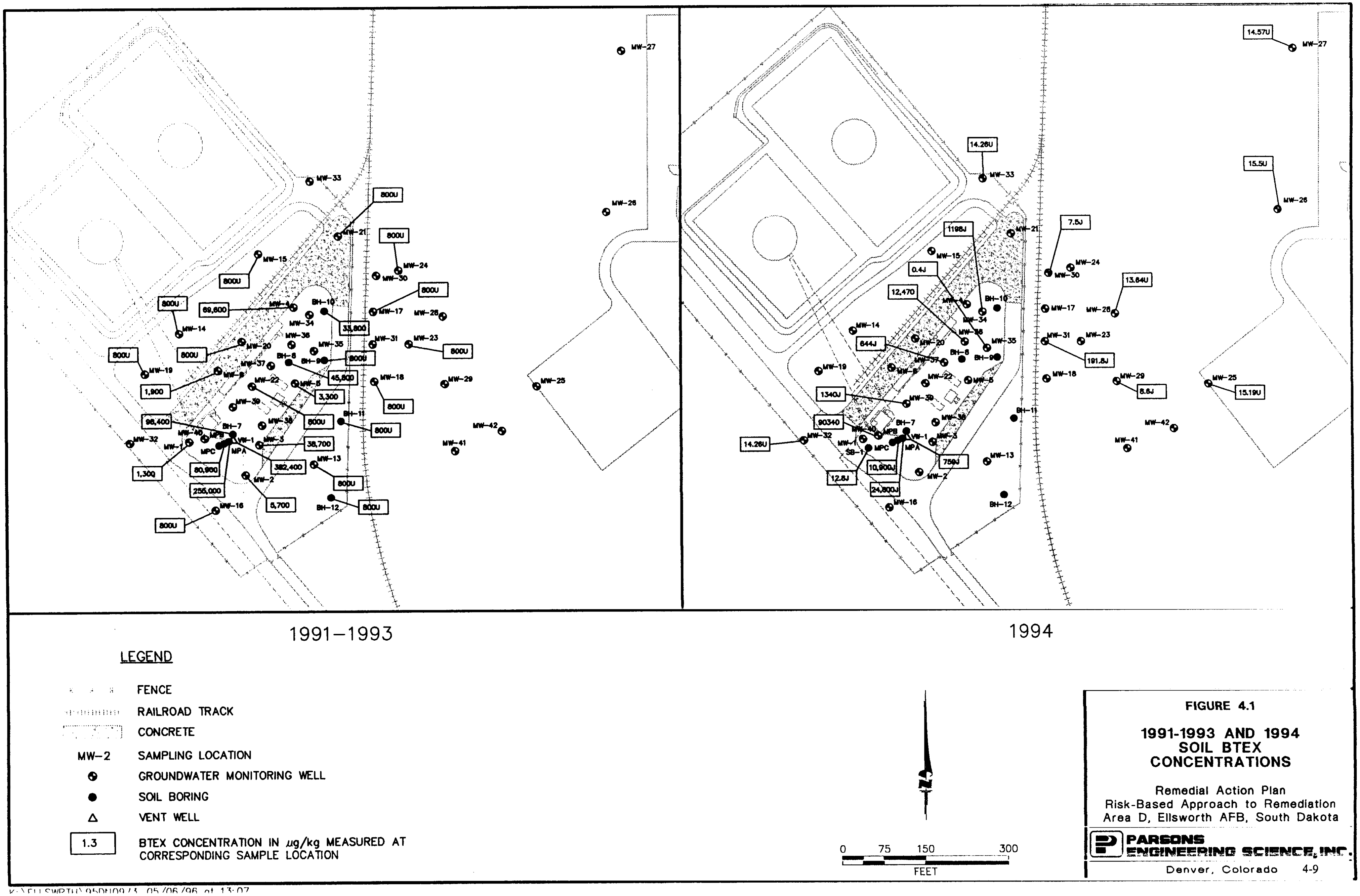

FIGURE 4.1

1991-1993 AND 1994 SOIL BTEX CONCENTRATIONS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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TABLE 4.4
ANALYTICAL RESULTS FROM PREVIOUS SOIL SAMPLING EFFORTS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	MW-1	MW-2	MW-3	MW-4	MW-5	MW-6	BH-7	BH-8
Collection Date	(1991)	(1991)	(1991)	(1991)	(1991)	(1991)	(1991)	(1991)
Sample Depth (feet bgs)	9-11	15-17	8-10	25-27	20-22	24-26	4-6	20.5-22.5
Parameter:								
Benzene (mg/kg)	0.2 U	0.2	0.4 U	0.3	0.2 U	0.2 U	0.4	0.2 U
Toluene (mg/kg)	0.2 U	0.3	6.3	17	0.3	0.2 U	2.0	6.1
Ethylbenzene (mg/kg)	0.2	1.3	5.4	9.3	0.2 U	0.3	15	5.7
Xylenes (mg/kg)	1.1	3.9	27	43	3.0	1.6	81	34
BTEX (mg/kg)	1.3	5.7	38.7	69.6	3.3	1.9	98.4	45.8
TRPH (mg/kg)	1,215	1,200	964	2,020	324	130	3,010	1,170

Sample Location	BH-9	BH-10	BH-11	BH-12	MW-13	MW-14	MW-15	MW-16
Collection Date	(1991)	(1991)	(1991)	(1991)	(1991)	(1991)	(1991)	(1991)
Sample Depth (feet bgs)	14-16	25-27	4-6	20-22	9-10.5	50-51.5	24-25.5	14-15.5
Parameter:								
Benzene (mg/kg)	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U
Toluene (mg/kg)	0.2 U	1.7	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U
Ethylbenzene (mg/kg)	0.2 U	8.1	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U
Xylenes (mg/kg)	0.2 U	24	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U
BTEX (mg/kg)	0.8 U	33.8	0.8 U	0.8 U	0.8 U	0.8 U	0.8 U	0.8 U
TRPH (mg/kg)	10 U	1,660	10 U	10 U	2.5	1.0 U	1.0 U	1.0 U

TABLE 4.4 (Continued)
ANALYTICAL RESULTS FROM PREVIOUS SOIL SAMPLING EFFORTS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location Collection Date Sample Depth (feet bgs)	MW-17 (1991) 19-20.5	MW-18 (1991) 14-15.5	MW-19 (1992) 9-10.5	MW-20 (1992) 14-15.5	MW-21 (1992) 19-20.5	MW-22 (1992) 9-10.5	MW-23 (1992) 19-20.5	MW-24 (1992) 19-20.5
Parameter:								
Benzene (mg/kg)	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	<0.2	0.2 U	0.2 U
Toluene (mg/kg)	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	<0.2	0.2 U	0.2 U
Ethylbenzene (mg/kg)	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	<0.2	0.2 U	0.2 U
Xylenes (mg/kg)	0.2 U	0.2 U	0.2 U	0.2 U	0.2 U	<0.2	0.2 U	0.2 U
BTEX (mg/kg)	0.8 U	0.8 U	0.8 U	0.8 U	0.8 U	0	0.8 U	0.8 U
TRPH (mg/kg)	1.0 U	1.0 U	1.0 U	242	1.0 U	2724	1.0 U	1.0 U

Sample Location Collection Date Sample Depth (feet bgs)	VW-1 (1993) 4-6	MPA (1993) 10	MPB (1993) 10	VW-1 (1994) 4-6	MPA (1994) 10	MPB (1994) 10
Parameter:						
Benzene (mg/kg)	6.4	15	3.2	0.063 U	0.058 U	0.19
Toluene (mg/kg)	13	10	3.7	0.063 U	0.058 U	0.059 U
Ethylbenzene (mg/kg)	53	40	17	0.063 U	3.7	1.7
Xylenes (mg/kg)	310	190	57	0.57	21	9
BTEX (mg/kg)	382.4	225	80.9	0.759	24.8	10.9
TRPH (mg/kg)	840	3,310	4,340	177	5,100	3,040

Sources: FMG, 1991 and 1992; ES, 1993a.

Three discrete soil samples also were collected near BH-7 during installation of the pilot bioventing system at the site in August 1993. The concentrations of total BTEX in these soil samples were significantly greater than those measured in any soil sample collected as part of the 1991/1992 fuel spill survey. The maximum 1993 concentration of total BTEX measured in soil was 382.4 mg/kg at VW-1. The minimum concentration of total BTEX measured in soil was 80.9 mg/kg at MPB. As noted in Section 1.2.2, total xylenes accounted for between 70 and 80 percent of the total BTEX in contaminated soils sampled in August 1993. These soil analytical results also are included on Table 4.4 and Figure 4.1.

In August 1994, 1-year soil confirmation samples were collected near the pilot bioventing system to assess the efficiency of the system at removing BTEX mass from unsaturated soils at Area D. A significant reduction in the concentrations of BTEX in soil was measured. In 1 year of operation, the maximum concentration of total BTEX in soil was reduced from 382.4 mg/kg to 24.8 mg/kg near VW-1. These soil analytical results are included on Table 4.4 and Figure 4.1. A more detailed discussion of the bioventing system performance is presented in Section 7.3 of the RAP.

Twenty-one soil samples were collected from 16 new soil boreholes and analyzed for BTEX compounds as part of the 1994 risk-based remediation investigation. Individual BTEX compounds were detected in 12 of the 21 soil samples. The maximum concentration of total BTEX measured in soil in 1994 was 90.3 mg/kg at MW-40, which is located immediately southwest of Building 8215 (Figure 4.1). A maximum concentration of 0.64 mg/kg benzene was measured at this soil sampling location as well. Total xylenes accounted for approximately 80 percent of the total BTEX concentrations measured in contaminated soil samples.

Although BTEX compounds were detected in soil samples collected from most sampling locations within the southeastern-most grassy area at Area D, the concentration of total BTEX in soil samples collected at sampling locations immediately adjacent to Building 8215 were about two orders of magnitude greater than the concentrations measured at other sampling locations at the site. Only benzene and total xylenes were measured in soil in 1994 at concentrations equal to or above the conservative contaminant screening criteria. All of the analytical soil sampling results for BTEX measured during the 1994 investigation are presented in Appendix A.

4.4.2 Soil Gas Sampling Results

Soil gas samples can be used for supplemental confirmation of the nature and extent of soil contamination at a site. Soil gas samples can be used to obtain a better representation of soil contamination because the sample is extracted from a larger volume of soil than discrete soil grab samples collected from a split spoon. Analytical results from discrete soil samples are usually nonhomogenous and can vary greatly from sampling location to sampling location. Thus, soil gas samples provide a valuable indication of the average type and magnitude of VOC contamination in the soil surrounding the soil gas probes.

Soil gas samples were collected during installation of the pilot-scale bioventing system in 1993, and during the 1-year bioventing test in August 1994. In 1993, the maximum concentration of benzene in soil gas was 290 parts per million of air (ppmv), which is equivalent to 942.5 milligrams per cubic meter of air (mg/m^3). The maximum concentration of total BTEX measured in soil gas in 1993 was 388 ppmv at MPA. However, after 1 year of system operation, the maximum concentration of benzene in soil gas had been reduced to 0.02 ppmv (0.065 mg/m^3), and the maximum concentration of total BTEX in soil gas had been reduced to 0.17 ppmv. These 1993 and 1994 soil gas samples are presented in Section 7.3.4.

Soil gas samples collected at Area D during the 1994 field effort were analyzed for BTEX compounds. Soil gas samples were collected from four locations within Area D (Figure 2.1). Benzene and toluene were detected in only one of the four soil gas samples collected at the site. Ethylbenzene was detected in two of the samples, and total xylenes were detected in three of four samples. These results are consistent with soil data collected at the site. The only detected concentration of benzene of 24 mg/m^3 was detected in the soil gas sample collected at SG-1. The only detected concentration of toluene of 0.11 mg/m^3 was measured at SG-6. The maximum concentrations of ethylbenzene and total xylenes, 22 mg/m^3 and 29 mg/m^3, respectively, were detected at SG-1.

These results correlate well with 1994 soil sampling analytical results, which indicate only isolated elevated levels of BTEX soil contamination. All of the recently measured soil gas concentrations for all of the BTEX compounds except the benzene detection at SG-1 are well below the time-weighted-average (TWA) 8-hour permissible exposure limits (PELs) (benzene: 3.25 mg/m^3, toluene: 375 mg/m^3, ethylbenzene: 435 mg/m^3, and total xylenes: 435 mg/m^3) defined for air contaminants by the Occupational Safety and Health Administration (OSHA). The benzene sample collected at SG-1 was withdrawn from a depth of 3.5 to 4 feet bgs. Flux measurements discussed in the next section quantify the concentration of contaminants emanating from the ground surface. However, if future excavation of these soils proves to be necessary to support remedial or construction activities, appropriate air monitoring, and personal protective equipment will be necessary to ensure that soil gas concentrations do not pose a risk to workers. All analytical results for soil gas samples collected during the 1994 field effort are presented in Table A.4 of Appendix A.

4.4.3 Soil Flux Sampling Results

Soil gas flux samples also were collected at Area D in August 1994, and analyzed for the volatile BTEX compounds. Analytical results for the soil gas flux samples were used to estimate the potential for gaseous emissions into the atmosphere. Sampling was completed in accordance with the procedures described in EPA's (1986) guidance document entitled *Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber*. Briefly, the calculation transforms concentration data into emission-rate data. The calculation sheets for soil gas flux samples collected at Area D are presented in Appendix A.

Low concentrations of toluene and xylenes were measured at all flux sampling locations (Figure 2.1). Ethylbenzene also was detected at low concentrations during flux testing at flux testing locations 1 and 2. Total xylenes from flux sampling location 1 were calculated to have the maximum emission rate of the all BTEX compounds measured during flux testing. The calculated emission rate of xylenes at flux testing location 1 was 11.1 micrograms per square meter per minute ($\mu g/m^2$-min). Interestingly, flux testing location 1 is upgradient from site contamination. The emission rate of toluene varied only slightly at all soil flux sampling locations, ranging from a maximum rate of 2.39 $\mu g/m^2$-min at location 2, which is adjacent to the sampling location resulting in the maximum measured BTEX soil concentrations, to a minimum of 1.5 $\mu g/m^2$-min at location 4, which is located east of the railroad tracks (Figure 2.1). Similar patterns in emission rates were observed for ethylbenzene.

Even assuming no atmospheric dispersion, these measured soil gas flux concentrations are well below the OSHA TWA 8-hour PELs for each specific compound. For example, the maximum concentration of total xylenes expected in the breathing zone over an 8-hour time period, assuming no atmospheric dispersion, would be 2.96 mg/m^3 (refer to Appendix E for calculation summary). This is significantly below the OSHA TWA PEL of 435 mg/m^3 for total xylenes. Based on these results, soil gas flux emissions do not represent a source of risk to onsite workers or off-site Base workers and residents. The low rates of emission suggest that the volatilization pathway and inhalation route are not significant at Area D.

4.5 GROUNDWATER CHEMISTRY

The following sections describe the results of groundwater sampling events conducted during the 1991/1992 fuel spill survey and the 1994 focused field investigation in support of a risk-based remediation of Area D. Only groundwater COPCs are described in detail. As discussed in previous sections, a small pocket of LNAPL was observed at the site during the 1994 sampling event. Remedial actions for the removal of the LNAPL at the site are discussed in Sections 7, 8, and 9 of this RAP. Discussion of dissolved constituents is presented below.

All of the groundwater monitoring wells at the site are screened across the entire saturated interval of the shallow aquifer. Apparent saturated thickness ranged from no evidence of groundwater to over 5 feet of saturated gravel. Background groundwater wells MW-16 and MW-32 are upgradient from and outside of the zone of contaminant influence.

4.5.1 Groundwater BTEX Contamination

Groundwater samples were collected and analyzed for the BTEX compounds at 16 permanent groundwater monitoring wells during both phases of the fuel spill survey (FMG, 1991 and 1992). Benzene was the only BTEX compound measured in groundwater above both the SDDENR promulgated groundwater quality standard of 5 $\mu g/L$ and risk-based contaminant screening criterion of 1.2 $\mu g/L$ (Table 4.2). The maximum concentration of benzene detected in groundwater at Area D during the 1991/1992 fuel spill survey was 2,675 $\mu g/L$ at MW-20. No residual LNAPL was noted at this sampling location when the well was installed (FMG, 1992), and no mobile LNAPL has been measured in MW-20. Elevated concentrations of total BTEX in groundwater were measured, with a maximum of 4,163 µg/L at MW-20. Ethylbenzene was the only other BTEX compound detected at a concentration (659 µg/L) that approached the most stringent risk-based contaminant screening criterion of 680 µg/L (Table 4.2). Table 4.5 summarizes the analytical data for BTEX compounds in groundwater at Area D collected during the 1991/1992 fuel spill survey. Figure 4.2 presents the probable extent of benzene and total BTEX in groundwater based on these data.

Groundwater samples collected at Area D in 1994 also were analyzed for the BTEX compounds. During the 1994 investigation, benzene was detected in groundwater samples collected from wells MW-6, MW-28, MW-29, MW-31, MW-34, MW-35, MW-39, and MW-40 at concentrations that exceeded the most stringent groundwater contaminant screening criterion (Table 4.2). The concentrations of benzene measured in groundwater at the site in 1994 above the most stringent contaminant screening criterion ranged from 1.8 µg/L at MW-28 to 3,400 µg/L at MW-39. Total BTEX concentrations in groundwater in 1994 ranged from below detection to a maximum of 5,375 µg/L at MW-6 (MW-6 contained LNAPL). Table 4.6 presents analytical results for each groundwater sample collected and analyzed during the 1994 risk-based remediation investigation that exceeded the most stringent groundwater contaminant screening criteria. A full report of the analytical results for the BTEX compounds in groundwater samples collected during the 1994 field effort is presented in Table A.6 of Appendix A.

Concentrations for benzene and total BTEX measured at each sampling location in 1994 are compared to concentrations for benzene and total BTEX measured during the 1991/1992 fuel spill survey in Figure 4.2. Five wells installed as part of the 1991/1992 fuel spill survey also were sampled in 1994. No BTEX compounds were detected in four of these wells (MW-13, MW-15, MW-16, and MW-23) during either the 1991/1991 or 1994 sampling events. The fifth well, MW-6, was not sampled in 1991/1992 because it was dry following installation and reportedly contained measurable levels of mobile LNAPL but no water in February 1992 (FMG, 1991 and 1992). Isoconcentration lines have been included on Figure 4.2 to characterize the probable extent of total BTEX contamination in groundwater during both sampling events.

The maximum concentration of dissolved benzene found in groundwater was 2,675 µg/L in 1991/1992. In 1994, the maximum dissolved benzene concentration of 3,400 µg/L was measured in newly installed MW-39, which is about 100 feet upgradient from MW-20 and approximately 80 feet south of MW-6. MW-39 is immediately adjacent to the JP-4 transfer lines near Building 8215. The maximum total BTEX concentrations ranged from 4,163 µg/L at MW-20 in 1991/1992 to 5,375 µg/L at MW-6 in 1994. In 1991/1992, the leading edge of the dissolved total BTEX plume appeared to have migrated just beyond MW-17. No contamination was reported in MW-23, MW-24, or MW-18. This means that detected concentrations of total BTEX in groundwater extended about 350 feet downgradient from the suspected source area in 1991/1992. Based on these data, approximately 2.2 acres of groundwater underlying

TABLE 4.5
ANALYTICAL RESULTS FROM 1991-1992 GROUNDWATER SAMPLING
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	MW-1	MW-2	MW-3	MW-4	MW-5	MW-13	MW-14	MW-15
Parameter:								
Benzene (µg/L)	10	0.8	0.5 U	440	0.5 U	0.5 U	0.5 U	0.5 U
Toluene (µg/L)	12	1	5 U	15	2.6	0.5 U	0.5 U	0.5 U
Ethylbenzene (µg/L)	36	0.6	0.5 U	280	0.5 U	0.5 U	0.5 U	0.5 U
Xylenes (µg/L)	59	27	1 U	1,680	20	1 U	1 U	1 U
BTEX (µg/L)	117	29.4	7 U	2,415	22.6	2.5 U	2.5 U	2.5 U
TPH (µg/L)	49	13,400	14,400	85,307	1,580	54	10 U	10 U

Sample Location	MW-16	MW-17	MW-18	MW-19	MW-20	MW-21	MW-23	MW-24
Parameter:								
Benzene (µg/L)	0.5 U	5 U	0.5 U	0.5 U	2,675	0.5 U	0.5 U	0.5 U
Toluene (µg/L)	0.5 U	5 U	0.5 U	0.5 U	12	0.5 U	0.5 U	0.5 U
Ethylbenzene (µg/L)	0.5 U	14	0.5 U	0.5 U	659	0.5 U	0.5 U	0.5 U
Xylenes (µg/L)	1 U	187	1 U	1 U	817	1 U	1 U	1 U
BTEX (µg/L)	2.5 U	201	2.5 U	2.5 U	4,163	2.5 U	2.5 U	2.5 U
TPH (µg/L)	10 U	4,862	10 U	10 U	10,440	31	26	10 U

Sources: FMG, 1991 and 1992.

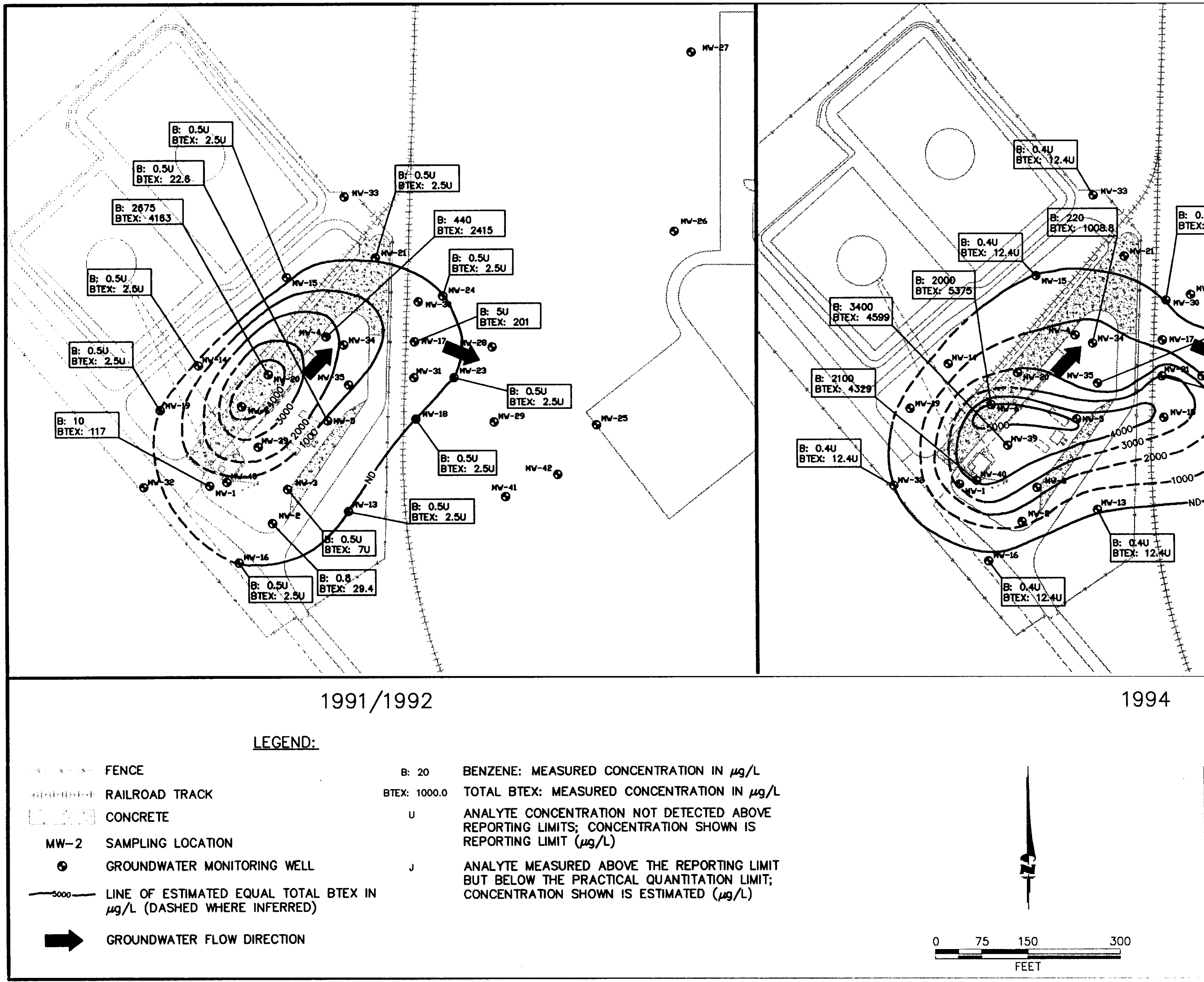
TABLE 4.6
DISSOLVED 1994 CONTAMINANT CONCENTRATIONS THAT EXCEEDED CONTAMINANT SCREENING CRITERIA
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Well	Benzene (μg/L) [a/]	Naphthalene (μg/L) [b/]	Total BTEX (μg/L)
MW-6	2,000	--[c/]	5,375
MW-28	1.9 J	--	5.5 J
MW-29	260	28	588.2
MW-31	1,500	180	3,678.30
MW-34	220	--	1,008.80
MW-35	200	160	972.8
MW-39	3,400	300	4,599
MW-40	2,100	230	4,329

[a/] Compared to risk-based screening criterion of 1.2 μg/L and SDDENR groundwater quality standard of 5 μg/L.

[b/] Compared to risk-based screening criterion of 280 μg/L and SDDENR groundwater quality standard of 10 μg/L (detection limit).

[c/] Not analyzed for PAH compounds.



LEGEND:

FENCE	
RAILROAD TRACK	
CONCRETE	
MW-2	SAMPLING LOCATION
⊕	GROUNDWATER MONITORING WELL
5000	LINE OF ESTIMATED EQUAL TOTAL BTEX IN $\mu g/L$ (DASHED WHERE INFERRED)
➡	GROUNDWATER FLOW DIRECTION
B: 20	BENZENE: MEASURED CONCENTRATION IN $\mu g/L$
BTEX: 1000.0	TOTAL BTEX: MEASURED CONCENTRATION IN $\mu g/L$
U	ANALYTE CONCENTRATION NOT DETECTED ABOVE REPORTING LIMITS; CONCENTRATION SHOWN IS REPORTING LIMIT ($\mu g/L$)
J	ANALYTE MEASURED ABOVE THE REPORTING LIMIT BUT BELOW THE PRACTICAL QUANTITATION LIMIT; CONCENTRATION SHOWN IS ESTIMATED ($\mu g/L$)

FIGURE 4.2

EXTENT OF DISSOLVED BENZENE AND TOTAL BTEX

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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and downgradient from Area D were impacted with dissolved total BTEX contamination at that time.

However, during the 1994 field investigation, dissolved total BTEX contamination was detected in newly installed MW-29. The 1994 analytical data for groundwater samples suggest that the plume extends at least 530 feet downgradient from the suspected source area, or approximately 180 feet further than in 1991/1992. No BTEX compounds were detected in the groundwater samples collected from MW-23 in either 1991/1992 or 1994. MW-23 is located immediately downgradient from MW-17 and apparently upgradient from MW-29 (Figure 4.2). Because no BTEX contamination was measured in MW-23 in 1991/1992, the extent of dissolved plume migration was believed to have been determined.

Site characterization data collected during the 1994 field investigation indicates the presence of hydrogeologic channels. Figure 4.3 presents a comparison of the dissolved total BTEX plume based on 1994 analytical data and an isopach map of gravel thickness across the site. Assuming that groundwater flows more readily through thicker gravel units, a preferential flow path or channel is present through the suspected source area, through MW-17, and toward MW-29. The gravel unit near MW-23 is not as thick as that found immediately to the southeast and east. The presence of this hydrogeologic channel, if it results in preferential flow and transport, would explain why the dissolved total BTEX plume flows to the north, away from the suspected source area, and then flows abruptly to the east. From MW-17 to MW-29, the dissolved plume actually appears to be moving toward the southeast, which is approximately 90° off of its direction of migration closer to the suspected source area.

Based on 1994 analytical data, about 5.2 acres of groundwater underlying and immediately downgradient of the suspected source area appears to be affected by elevated dissolved total BTEX. The apparent increase in the extent of dissolved contamination may be due to either plume expansion or incomplete delineation of the dissolved plume during the 1991/1992 investigation. LNAPL was measured at MW-6 during both investigations. This isolated pocket of LNAPL, which may be the result of an ongoing JP-4 fuel leak, is acting as a continuous source of groundwater contamination. The anticipated effects of the presence of LNAPL on groundwater quality at the site over time is quantitatively explored in Section 6.

4.5.2 Naphthalene Groundwater Contamination

No groundwater samples collected during the 1991/1992 fuel spill survey were analyzed for PAH compounds (FMG, 1991 and 1992). Groundwater samples collected in 1994, however, were screened for naphthalene on the basis of the chemical composition of the suspected contaminant source (Parsons ES, 1994a). Naphthalene was identified as an indicator PAH compound, because it is the only PAH compound that is generally likely to be present in JP-4. Naphthalene is listed by SDDENR as a "potential toxic pollutant" (Chapter 74:03:15:04). The promulgated groundwater quality standard for all "potential toxic pollutants" is below detection limits consistent with the analytical precision and sensitivity requirements specified by the SDDENR until such a time that a federal maximum contaminant level (MCL) is defined by EPA.

f 4.3

Therefore, the most stringent groundwater contaminant screening criterion was identified as the project-specific MDL for naphthalene (Tables 2.1 and 4.2).

Naphthalene was detected above the project-specific MDL in five of the six wells screened for PAH contamination at Area D. Naphthalene was detected in groundwater samples from monitoring wells MW-29, MW-31, MW-35, MW-39, and MW-40. No naphthalene was detected in the sample collected from background sampling location MW-16. The maximum concentration of naphthalene detected in groundwater in 1994 at Area D was 300 µg/L at MW-39, which also exceeds the risk-based contaminant screening criterion of 250 µg/L. Figure 4.4 shows the concentrations of naphthalene measured in groundwater during the 1994 sampling event. Based on these data, naphthalene may have migrated in groundwater as much as 500 feet downgradient from the suspected source area. All analytical results for naphthalene in groundwater collected during the 1994 field effort are presented in Table A.7 of Appendix A.

4.6 SUMMARY

Total BTEX contamination in soils at the site apparently is limited in areal extent, and is centered immediately adjacent to Building 8215 (i.e., near the pilot bioventing system). All of the BTEX compounds have been measured at concentrations above the conservative contaminant soil screening criteria during at least one of the soil sampling events, although only benzene and total xylenes were identified as soil COPCs based on 1994 soil analytical results. The need to remediate soil contamination at the site to protect human health and prevent further groundwater degradation is considered further in subsequent sections.

Based on 1994 analytical data, approximately 5.2 acres of groundwater have been impacted by JP-4-related contamination. The magnitude and extent of dissolved benzene and total BTEX groundwater contamination may be increasing at the site, possibly due to the presence of an isolated source of contaminant mass (i.e., small pocket of LNAPL in the vicinity of MW-6). It is possible that the dissolved plume has not migrated appreciably since the 1991/1992 investigation. Although the plume appears to have expanded in areal extent, the difference may be attributed to the degree of resolution. The areal extent of the dissolved plume in 1991/1992 may not have been fully characterized, even though it appeared to have been bounded, because of the presence of hydrogeologic channels. Future annual monitoring data will be used to determine if the plume is migrating.

Dissolved concentrations of naphthalene also were measured at the site in 1994. Wells analyzed for PAH contamination suggest that naphthalene may have migrated 500 feet downgradient from the source area.

The chemical fate of soil and groundwater COPCs based on their chemical characteristics and site-specific characteristics is considered quantitatively in Section 6. Emphasis is given to documenting the effects of natural physical, chemical, and biological processes on contaminant mass, concentration, persistence, toxicity, and mobility. The anticipated effects of LNAPL on groundwater quality over time also is

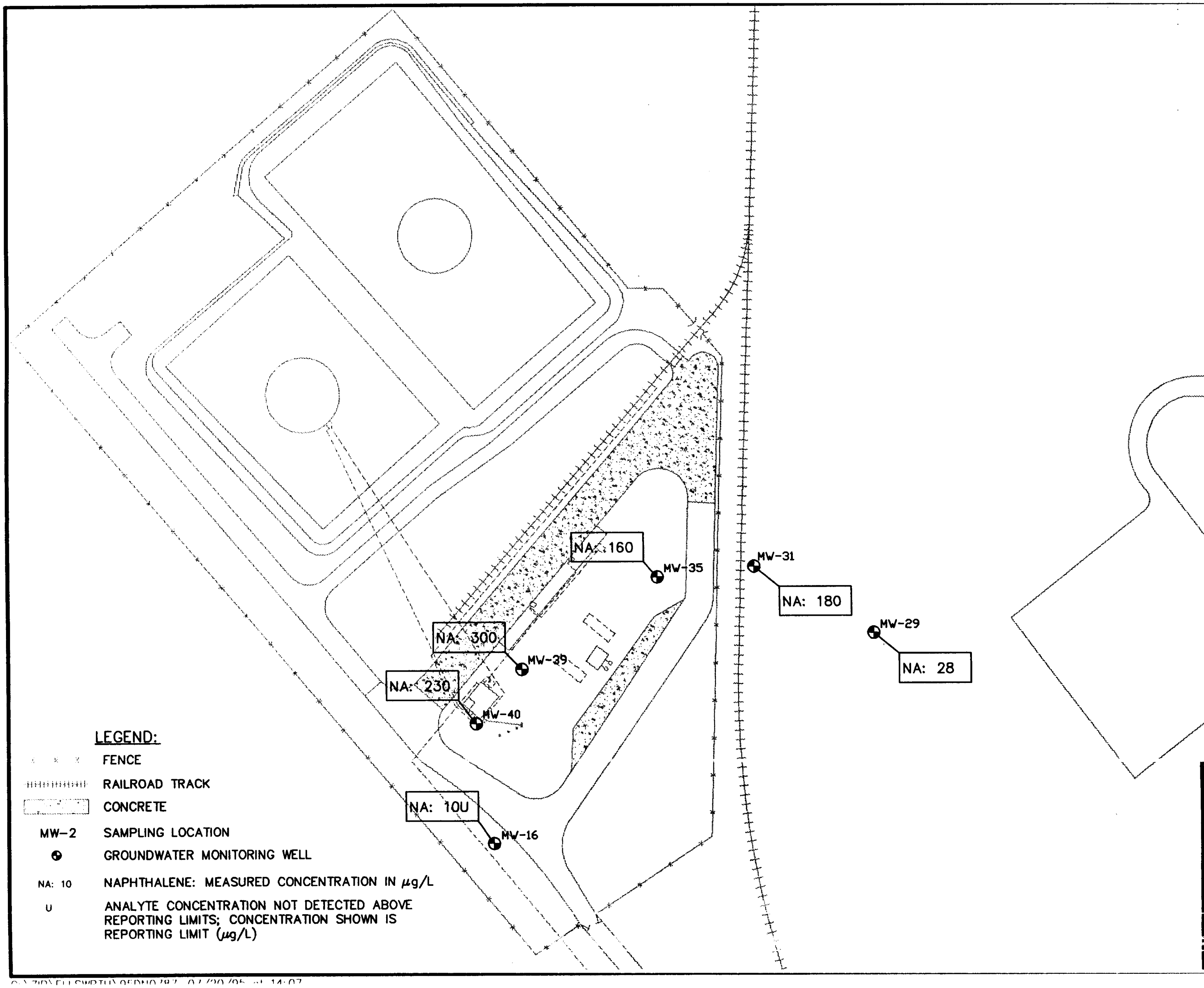
NA: 160
MW-35
MW-31
NA: 180
MW-29
NA: 28
NA: 300
MW-39
NA: 230
MW-40
NA: 10U
MW-16
N
0 25 50 100 200
FEET
LEGEND:
FENCE
RAILROAD TRACK
CONCRETE
MW-2 SAMPLING LOCATION
GROUNDWATER MONITORING WELL
NA: 10 NAPHTHALENE: MEASURED CONCENTRATION IN μg/L
U ANALYTE CONCENTRATION NOT DETECTED ABOVE REPORTING LIMITS; CONCENTRATION SHOWN IS REPORTING LIMIT (μg/L)

FIGURE 4.4

EXTENT OF NAPHTHALENE IN GROUNDWATER

Remedial Action Plan
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Area D, Ellsworth AFB, South Dakota

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

explored to define the type and magnitude of source removal activities that may be required to minimize further groundwater degradation and contaminant migration.

SECTION 5

PROPOSED DEGREE OF CLEANUP REQUIREMENTS

Section 4 discusses the nature and extent of contamination at the Area D and identifies COPCs based on the most stringent contaminant screening criteria (i.e., the most stringent risk-based criteria or promulgated standard). The risk-based contaminant screening criteria for soils and groundwater were calculated by assuming that the compound-specific concentrations in affected media should be sufficient to protect human health and the environment under the most conservative land use assumption (i.e., residential or unlimited use). Although implementation of this degree of remediation may be desirable and pursued to the extent possible, such cleanups should not be required at sites that are not planned or expected to be available for unrestricted activities at the completion of the remedial action.

The goal of the risk-based approach to remediation is to identify and implement an appropriate remedial action for Area D which is protective of the human health and the environment. To clearly identify a proposed remedial action for Area D, it was necessary to assess what level of risk reduction would be necessary to protect potential human and ecological receptors, given the current and foreseeable uses of the site and natural resources in question. Legally applicable or relevant and appropriate federal and state public health and environmental requirements were also considered as possible cleanup objectives.

5.1 EXPOSURE PATHWAY ANALYSIS

An exposure pathway analysis describes the course a chemical takes from the source of contamination to a potentially exposed individual (EPA, 1989a). A completed exposure pathway must consist of a source, a release mechanism (e.g., leaching, volatilization), a transport medium (e.g., groundwater, air), a potential human or ecological receptor (e.g., current onsite workers, potential future onsite workers, current and future offsite receptors), a potential exposure point (i.e., locations where receptors could come into contact with site-related contamination), and potential routes of exposure (e.g., ingestion, inhalation). Each of these elements must be present if a particular exposure pathway is to be considered complete. If any one of these elements is missing, the exposure pathway is considered incomplete and there is no risk. Site-related contamination can only present a potential risk to receptors if exposure pathways are complete.

A site-specific exposure pathway analysis was completed for Area D to determine the likelihood of human or ecological contact with site-related contamination. The first step in the exposure pathway analysis was to conduct a qualitative screening of potential pathways. The objective of this screening assessment was to determine which, if any, exposure pathways are complete (EPA, 1992a). Emphasis was given to identifying those pathways where contaminants are released and may migrate within the environment, but potential receptors currently do not come into contact with these chemicals and are not likely to do so in the future. These incomplete exposure pathways were eliminated from further consideration. Exposure pathways that presented negligible risks also were identified. The remedial requirements for Area D will not be developed to address chemical contamination that does not pose an actual risk to human health or the environment.

Those exposure pathways that were considered complete and significant as a result of the qualitative screening assessment were retained for quantitative evaluation. A quantitative evaluation of the type of contaminant released from a site, the impact on environmental media, and the environmental transport and transformation of contaminants following such a release was then conducted for potentially complete exposure pathways. Resultant concentrations of COPCs were then used to evaluate the likely implications to human health or the environment. The effects of various remedial technologies on eliminating potentially complete exposure pathways, or at least minimizing exposure point concentrations, was investigated. The remedial action recommended for implementation at the site was designed to reduce the potential risks posed by site-related contamination based on site-specific conditions (SDDENR, 1994).

5.1.1 Conceptual Site Model

A conceptual site model (CSM) is used to define the type of potential exposure to contaminants at and migrating from a site (i.e., used to systematically evaluate the impact of site COPCs in relevant media on potential receptors). The CSM qualitatively describes each onsite release point, the types of contaminant transport and fate mechanisms that may be involved at the site, each group of potentially exposed populations or receptors, and how each receptor group could come into contact with site-related contamination. The CSM is used to summarize existing site characterization data, including assumptions about land and groundwater use, and to complete the qualitative exposure pathway screening assessment. A preliminary CSM for Area D, which was used to guide data collection activities, is included in the work plan (Parsons ES, 1994). The final CSM for Area D (Figure 5.1), which is developed in the following sections, incorporates data collected during the site investigation conducted in August through November 1994 into the preliminary CSM.

5.1.1.1 Source and Release Mechanisms

The first component of the CSM is contaminant release screening. The likelihood of release from a source, the nature of the contaminants involved, and the probable magnitude of their release must all be considered (EPA, 1989a and 1992a). The source of chemical contamination at the site is suspected to be a subsurface release of JP-4 from fuel transfer lines at the site. Jet fuel was apparently released to soils and possibly underlying groundwater from a leaking transfer line or storage tank. The system at Area D failed a pressure test in 1990. Based on site data collected in 1994 under the risk-based field investigation and the 1995 baildown test, either a more recent one-time release may have occurred or the initial leak discovered in 1990 has not yet been eliminated. Jet fuel apparently percolated through unsaturated soil and collected on the water table. Variable levels of free product in both residual and mobile phases f 5.1

have been encountered at the site. Although residual LNAPL was reported to be present in MW-4 and BH-7 during the 1991/1992 fuel spill survey (FMG, 1991 and 1992), this could not be confirmed during the 1994 investigation (Section 4.2). Variable levels of mobile LNAPL have been measured in MW-6 since 1992, as discussed in Sections 1.2 and 4.2. Table 4.1 lists the measured concentration of each of the BTEX compounds in mobile product collected at MW-6. These analytical data indicate that high concentrations of contaminants persist in the mobile LNAPL at the site. This contaminant mass can partition from (weather from) the isolated pocket of LNAPL in the vicinity of MW-6 into underlying soils and groundwater, acting as a continuous source of contamination to the environment.

Soil sampling and analysis completed as part of the 1991/1992 fuel spill survey, and when the pilot bioventing system was installed at the site in 1993, indicated elevated concentrations of all of the BTEX compounds in unsaturated soil. Subsurface soil sample locations were selected during both of these sampling events to target soils having the highest potential for soil contamination. The objective of the 1991/1992 soil sampling event as to estimate the probable location of a subsurface fuel release. The 1993 sampling event considered these soil data when identifying an appropriate location to test the effectiveness of *in situ* bioventing. Thus, the soil results from the 1993 sampling event represent baseline soil contaminant concentrations in the suspected release area prior to implementing a pilot-scale engineered soil remedial technology.

A total of 48 soil samples were collected during the 1991/1992 fuel spill survey, the 1993 initial bioventing pilot test, the 1994 one-year bioventing pilot test, and the 1994 risk-based site investigation. Figures 2.2 and 4.1 show locations of soil samples collected during each of the sampling events. Figure 4.1 shows the compound-specific analytical results for soil samples collected at the site to date. Table 4.4 and Appendix A combined contain a complete list of soil samples and associated depth intervals collected during all sampling events.

Of the 48 soil samples collected from this site, 21 soil samples were collected from the suspected source area, 23 soil samples were collected from downgradient locations, and 4 were collected from upgradient locations. Twenty-seven of the soil samples had detections of one to all of the individual BTEX compounds. During the 1991/1992 fuel spill survey, all of the BTEX compounds were measured in soil at concentrations exceeding the conservative contaminant criteria calculated to protect groundwater from adverse impacts due to leaching. Benzene was measured in soil at concentrations above the most conservative contaminant screening criterion (leaching) in 3 of the 24 soil samples. Toluene, ethylbenzene, and total xylenes were measured at concentrations above the chemical-specific leaching screening criterion in 3, 5, and 1, respectively, of the 24 soil samples.

All of the BTEX compounds were measured at concentrations above its leaching screening criterion in each of the 3 soil samples collected near the pilot bioventing system in 1993. The only exception was total xylenes at MPB (57 mg/kg), which is slightly below the leaching criteria of 74 mg/kg. The concentration of each of the BTEX compounds at this sampling location was markedly reduced during the 1-year bioventing pilot test (Section 7). During the 1994 sampling event in support of the risk-based remediation of Area D, benzene, ethylbenzene, and total xylenes were measured in soil at concentrations above the chemical-specific leaching screening criterion in areas outside of the bioventing system radius of influence. Both benzene and ethylbenzene were measured in 2 of the 19 soil samples at concentrations above the leaching screening criterion. Total xylenes exceeded its leaching criterion in only 1 of the 18 soil samples analyzed in 1994.

Based on the data collected to date, it appears that both mobile and residual LNAPL and contaminated soils may be a significant source of chemical contamination at the site. Possible release mechanisms from the soil and LNAPL include volatilization and leaching. Chemicals most likely to be released via these mechanisms will be volatile and water soluble. Because BTEX compounds are volatile and highly to moderately water soluble, they are the most probable chemicals that will be released from mobile or residual LNAPL and soils into environmental media at the site. A more detailed evaluation of the nature and magnitude of chemical releases expected at the site is presented in Section 6.

5.1.1.2 Contaminant Environmental Transport and Fate

The second component of the CSM is a screening assessment of contaminant transport, transformation, and fate in the environment following release. This screening step involves identifying each type of transport process that may govern the movement of contaminants within and among environmental media, determining the direction and general rate of contaminant movement from the site, and defining the areas to which contaminants may have been or are expected to be transported (EPA, 1992a). This screening analysis is designed only to identify likely pathways of contaminant migration. An in-depth, quantitative evaluation of contaminant transport, transformation, and fate over time and distance at Area D is presented in Section 6.

Volatilization of chemicals from contaminated media into the atmosphere is a possible release/transport mechanism at the site. However, the aboveground soil flux data collected during the 1994 investigation indicates that adverse air quality impacts due to chemical volatilization was not likely to be significant (Section 4.4.4 and 4.4.5). This exposure pathway will be eliminated from further consideration. Additionally, only very low concentrations of all of the BTEX compounds except benzene were measured in subsurface soil gas samples. Benzene was detected in a soil gas sample collected at MPA in 1992 at a concentration above the OSHA 8-hour TWA PEL; however, soil gas concentrations at this same sampling location had been effectively reduced below detection by 1993 as a result of bioventing. Benzene was also detected in a soil gas sample collected at SG-1 in 1994 at a concentration above the OSHA 8-hour TWA PEL. However, subsurface soil gas concentrations are not representative of an exposure concentration for onsite intrusive workers engaged in deep excavation activities, because it does not account for the volatilization that could occur during excavation of soils. Nonetheless, if future excavation of these soils proves to be necessary, appropriate air monitoring and personal protective equipment will be required to ensure that construction workers in deep trenches are not exposed to adverse soil gas levels. Implementation of bioventing, which will reduce soil gas concentrations at the site, is another approach to protect hypothetical onsite construction workers from adverse exposures.

Benzene was the only BTEX compounds detected in soil samples collected during the 1991/1992 fuel spill survey, the 1993 bioventing pilot test, and the 1994 sampling events at concentrations above the contaminant screening criterion calculated to eliminate potential health risks due to inhalation of fugitive soil particles (Table 4.2). Benzene exceeded the health-based screening criterion for inhalation in all of the soil samples collected in 1993 near the pilot bioventing system. Benzene was measured above the health-based screening criterion for inhalation in two of the 18 soil samples (i.e., 9 to 10 feet bgs and 13.5 to 14.5 feet bgs at MW-40). However, it is important to note that the contaminant screening criterion developed to protect against risks due to inhalation of contaminated soil particles is based on an unlimited or residential land use scenario. The nature and type of exposure to fugitive dusts under an industrial land use scenario will be different. Additionally, contaminated soils at Area D are protected from potential atmospheric erosion by overlying uncontaminated clayey soils, grass, concrete, asphalt and gravel driveways and parking areas, and on-site buildings. It is unlikely that exposure pathways involving fugitive dust will be significant at this site. Thus, contaminant transport from soils via fugitive dust generation will not be retained in the final CSM for evaluation.

Groundwater data collected as part of the 1991/1992 fuel spill survey and the 1994 field investigation and presented in Section 4 confirm that chemicals have been released into groundwater at the site. November 1994 groundwater elevation data suggest that groundwater flow at the site is toward the northeast (Figure 3.6). However, the 1994 site data also suggest that preferential dissolved contaminant transport pathways may exist at the site as a result of hydrogeologic channels (Section 4.5.1). As described in Section 4.5.1. dissolved contaminants may be migrating preferentially through thicker gravel units at the site. The presence of these hydrogeologic channels may explain why the dissolved plume has migrated to the northeast from the suspected source area and then takes a sharp turn toward the east-southeast (Figure 4.3). The general direction groundwater migration is an important component of the final CSM. These data are critical to identifying the groups of potential human and ecological receptors that could be exposed to site-related contamination as it is transported in groundwater.

The maximum linear advective groundwater velocity was calculated to be 0.4 ft/day, or 146 ft/year (Section 3.4.2). Assuming that groundwater migrates at this velocity along these hydrogeologic channels, it would take a minimum of 72 years for contaminated groundwater at the Area D to migrate to the nearest downgradient Base boundary, which is located approximately 2 miles to the southeast of the source area. The Base boundary is the first possible exposure point for contaminated groundwater since no groundwater wells used to meet potable water supplies are located on-Base (Section 3.6.4).

If the effects of intrinsic remediation processes such as adsorption and biodegradation are not considered during this initial screening step, it is possible that site-specific contamination could eventually migrate in groundwater to areas beyond Base control. This is an extremely conservative exposure assumption. The actual extent of contaminant transport and the effects of intrinsic remediation on dissolved contaminant concentration, mass, mobility, persistence, and toxicity (i.e., toxicity of chemical could change as it transforms to compounds like carbon dioxide and water) must be quantitatively investigated using both historical monitoring data and numerical fate and transport models. For the purposes of this screening assessment, however, it has been conservatively assumed that dissolved contaminants could eventually migrate in groundwater to areas beyond the Base boundary. Contaminant transport in groundwater is considered a potential pathway for contaminant movement in the environment for Area D.

No bodies of surface water are present in the immediate vicinity of the Area D. As described in Section 3.1, the nearest surface water bodies located downgradient from the leading edge of dissolved contamination are Bandit, Heritage, Gateway, and Golf Course Lakes. The nearest of these on-Base surface water bodies is about 2,600 feet southeast of the leading edge of the Area D plume. Given the maximum linear advective velocity of groundwater at the site (i.e., 0.4 ft/day), it would take contaminated groundwater about 25 years to migrate in groundwater to and possibly discharge into the nearest surface water body. However, on-Base surface water bodies are considered ephemeral, and eventually discharge into Box Elder Creek, which is also considered ephemeral (USAF, 1994). Ephermal drainageways contain water only when sufficient runoff is available to support flow. Typically these streams conduct water only during or immediately following precipitation events. Because of the depth to groundwater surface at the Base (i.e., typically at least 15 to 30 feet bgs), such flow patterns suggest that these surface water bodies are primarily fed by overland precipitation and not groundwater influx. It is unlikely that contaminated groundwater would actually discharge into these ephermal surface water bodies, even if it were to migrate 2,600 feet further downgradient. Thus, for the purposes of this screening assessment, contaminant transport in groundwater to downgradient surface water bodies is not considered a reasonable pathway for contaminant movement in the environment for Area D and has been eliminated from the final CSM.

Despite the recharge characteristics of the ephermal surface water bodies on the Base, transport of contaminants in surface runoff to receiving surface water bodies is not expected to be significant mechanism controlling contaminant environmental fate at the site. Elevated concentrations of soil COPCs were measured in soil samples collected at least 10 feet bgs. Because of the nature of the source (an underground fuel transfer line or tank leak) and the depth of soil and LNAPL contamination, the potential for precipitation to become contaminated due to contact with contaminated environmental media is very low. Therefore, transport to surface water via precipitation runoff has been eliminated from further consideration.

5.1.1.3 Potentially Exposed Populations

The final major component of the CSM for Area D is the identification of potentially exposed populations. The objective of this step is to draw upon the results of the contaminant fate screening assessment to qualitatively determine the likelihood and extent of human or ecological population contact with site-related contaminants (EPA, 1989a and 1992a). Land use assumptions are critical to defining the types of receptors that are now present or may be present in the foreseeable future at Area D or in immediately adjacent areas and areas outside Base property which could be impacted by site-related contamination.

5.1.1.3.1 Current Onsite Conditions

As described in Section 3.6.2, the site is currently on an active Base and maintained as an active fuel supply yard. Area D is within an access-restricted area. The likelihood of unauthorized access at the site has been severely reduced due to the Base perimeter fence and the locked perimeter fence around the site proper. Onsite workers conservatively would have very limited contact time with site environmental media. Worker activities are primarily associated with storage and transfer of jet fuel, and possibly grounds maintenance such as grass mowing. No groundwater is withdrawn from areas within or immediately adjacent to Area D to meet potable or nonpotable water requirements. The water supply for Base facilities is currently derived from the Rapid City Water Service (Section 3.6.4).

The contaminant release and transport screening assessments showed that soils and groundwater are the environmental media that could possibly be involved in complete and significant exposure pathways (Figure 5.1). Data demonstrate that volitilization from soils is not a significant contaminant release mechanism. The potential exposure pathway involving release of fugitive dusts to the atmosphere is insignificant and incomplete due to site surface features and depth to contaminated soils. Impacts to downgradient surface water bodies is not anticipated because the streams/lakes are apparently only fed from precipitation runoff. The industrial nature of the site, which includes concrete and asphalt driveways and parking areas, building structures, and chain link fencing to limit access, precludes the existence of suitable on-site wildlife habitat. Additionally, the continuous industrial use of this site and the perimeter fencing prohibits free-ranging animals from becoming permanent inhabitants of Area D. Finally, the extent of impermeable, man-made surface cover and depth to soil contamination and groundwater (e.g., 13 to 28 feet bgs) prohibits burrowing animals or phreatic plants from being exposed to contaminated environmental media. No pathways involving aquatic life are complete.

Therefore, current onsite worker populations could only be exposed to site-related contamination via soils and groundwater. However, since groundwater is not extracted and used by onsite workers to meet potable or nonpotable water demands, these worker populations do not come into contact with groundwater contamination. Even if these workers were to engage in construction activities requiring excavation, the depth to contaminated soils and the groundwater surface (i.e., 13 to 28 feet bgs) would make even incidental contact unlikely. Onsite workers could only be exposed to soils and groundwater contamination as a result of deep construction/excavation activities within source area and the dissolved plume area at Area D. Consequently, it is reasonable to assume that all exposure pathways to onsite receptors are incomplete under current conditions.

5.1.1.3.2 Current Offsite Conditions

Area D is surrounded by light and heavy industrial areas and open space within the Base. Dissolved groundwater contamination appears to be migrating in the east-southeast direction along preferential hydrogeologic channels. The area immediately to the east and southeast of the site is an open field. An intramural field and running track is located at the far southern edge of this field. The nearest occupied area to the southeast of Area D is an on-Base commercial restaurant, which is located about 2,600 feet southeast of the site perimeter fence. All areas beyond this on-Base commercial facility to the nearest Base Boundary to the southeast of the site may be classified as light to heavy industrial areas. No site-related contamination has migrated more than 250 feet beyond the fenced perimeter of the source area, as indicated by 1994 sampling results. This means that offsite and off-Base populations could not come into contact with site-related contamination. All exposure pathways to offsite and off-Base populations are incomplete under current conditions.

5.1.1.3.3 Future Conditions

As described in Section 3.6.3, no change in onsite land use or land use in areas immediately downgradient is planned. All receptor groups and their activities should remain identical to current conditions. This is important because it means that all reasonable future exposure pathways to on-Base receptors will remain incomplete. Future onsite and off-site Base workers could only be exposed to soil and groundwater contamination as a result of deep construction/excavation activities. The extent of groundwater that may be impacted by site-related contamination in the future depends on contaminant transport, transformation, and fate mechanisms. The anticipated extent of groundwater contamination at and downgradient from Area D over time is quantitatively explored in Section 6. These data will be used to determine where future construction workers engaged in excavation activities could incidentally contact contaminated soils and groundwater. However, for all intents and purposes, all exposure pathways to probable onsite receptors should remain incomplete under foreseeable land use conditions.

If site-related contaminants were to be transported with and at the same linear velocity as groundwater (assuming no intrinsic remediation), groundwater contamination could migrate beyond the southeast Base property boundary within 72 years (Section 5.1.1.2). As discussed previously, all areas downgradient from Area D are used to support light to heavy industrial operations. The area directly beyond the southeastern Base property boundaries is zoned as both residential and commercial (Section 3.6.2). Because of the widespread use of shallow groundwater wells to meet potable water demands, potential exposure pathways involving shallow groundwater were investigated in more detail. The objective of this evaluation was to determine the nature and magnitude of remediation activities that may be warranted at the site to eliminate potential future exposure pathways involving shallow contaminated groundwater. This quantitative assessment is presented in Section 6.

5.1.2 Summary of Potentially Completed Exposure Pathways

Figure 5.1 presents the final CSM, which incorporates the results of the site-specific exposure pathway screening assessment. Exposure to onsite contamination in soils and groundwater is only possible if deep excavation/construction activities are conducted in and immediately downgradient from the source area at Area D. Therefore, onsite intrusive workers are the only group of receptors that could come into contact with site-related contamination and only if/when deep excavation/construction activities are conducted. This exposure pathway will not be complete as long as appropriate exposure control measures are implemented at the site.

The only exposure pathway that may be complete at this site would involve potential ingestion of contaminated groundwater that has migrated off-Base. This exposure pathway was retained based on an extremely conservative, qualitative evaluation of contaminant transport in groundwater. Section 6 presents a quantitative fate and transport analysis using monitoring data and the numerical groundwater flow and contaminant transport model Bioplume II. The effects of transformation processes and other contaminant characteristics that influence contaminant concentration, mass, mobility, persistence, and toxicity are factored into this thorough analysis.

The conclusions of this site-specific exposure pathways analysis are important for several reasons. First, the screening assessment demonstrates that, even under extremely conservative assumptions, current concentrations of COPCs in soil and groundwater at the site do not pose a risk to human health because no potential exposure pathway is complete. This is important because it shows that active remediation is not necessary to minimize or eliminate any imminent risks. Second, the screening assessment shows that groundwater contamination could take up to 72 years to migrate to the Base property boundary. This gross estimate of contaminant travel time assumes that all contaminants migrate as fast as groundwater and are not subject to the intrinsic remediation processes described in Section 6. This is important because it shows that onsite groundwater contamination does not pose an immediate threat to downgradient media. Third, the screening assessment indicates that only future exposure pathways involving groundwater may be complete and significant for the Area D. This type of information helps to focus the range of remedial objectives and requirements.

5.2 PROPOSED TYPE OF CLEANUP

The Air Force intends to implement a risk-based remedial action at Area D that is sufficient to minimize contaminant migration and eliminate potential risks to human health and the environment. This type of remedial action is consistent with the new site classification developed by SDDENR (1994) called inactive status. According to the SDDENR (1994), sites classified as inactive may be contaminated above state standards but contaminant levels cannot be increasing and cannot pose a significant health or environmental threat. If a site is classified as inactive, no additional monitoring or active remediation will be required at the site. The proposed remedial action must be sufficient to prevent site-related contaminants from migrating at concentrations above state standards to areas beyond appropriate exposure controls. It also is possible that state promulgated groundwater quality standards (Chapter 74:03:15) could be fully achieved at the site over time. However, meeting state groundwater quality standards at every point in the impacted area is neither a requirement or goal of this RAP if it is not necessary to protect human health and the environment.

5.2.1 Risk-Based Remedial Goals for Contaminated Soils and Groundwater

On the basis on the exposure pathway analysis summarized in Figure 5.1, site-related contamination does not pose a risk to human health and the environment at this time because no exposure pathway is complete unless deep excavation activities are conducted at the site. The site and the land immediately downgradient from Area D are used as light to heavy industrial areas and access restrictions are enforced. To achieve inactive status classification pursuant to SDDENR (1994) guidance, it is necessary to demonstrate that contaminant concentrations are not increasing and do not pose a risk to human health and the environment. To accomplish this, the level of contamination that can remain in soils and groundwater at the site that will not pose a risk to onsite workers engaged in deep excavation/construction activities or cause exposure pathways downgradient from Area D to be completed sometime in the future must be defined.

Table 5.1 presents risk-based target remedial goals for contaminated soils and groundwater appropriate for Area D. These numerical concentration goals are based on carcinogenic and/or noncarcinogenic toxicity values and exposure assumptions appropriate for an industrial setting. The only sources of toxicity information included the Integrated Risk Information System (IRIS) (Micromedix, Inc., 1995) and the Health Effects Assessment Summary Tables (HEAST) (EPA, 1994). Risk-based remedial goals incorporate were developed using the procedures described in EPA (1991a) OSWER Directive 9285.7-01B entitled *Human Health Evaluation Manual, Part B: Development of Risk-Based Preliminary Remediation Goals* and EPA (1991b) OSWER Directive 9481.00-6C entitled *Risk Assessment Guidance for Superfund: Volume I - Human Health Evaluation Manual, Part C: Risk Evaluation of Remedial Alternatives.* Additional recent EPA guidance relevant to developing risk-based remedial goals that protect human health and the environment also were used (EPA, 1989a, 1989b, 1991c, 1994).

Risk-based goals for onsite media for known or suspected carcinogens were calculated to define the level of residual site contamination that represents an excess upperbound cancer risk of between one in 10,000 (10^{-4}) and one in one million (10^{-6}) for workers engaged in light to heavy industrial/construction activities at the site. Similarly, risk-based goals for systemic toxicants were calculated to eliminate any appreciable risk of deleterious effects to workers that could be incidentally exposed to contaminated media. The derivation of these risk-based remedial goals, including the algorithms and exposure assumptions, are presented in Appendix G.

Cross-media contamination of groundwater from contaminated soil also was factored into the development of the risk-based goals for soils (Table 5.1). The impacts of site-related contaminants from soils into groundwater at Area D is quantitatively explored in Section 6.6.1 based on site-specific data. Residual contaminant concentrations for groundwater underlying and immediately downgradient from Area D that will be sufficient to ensure that the dissolved contaminant plume does not migrate at hazardous concentrations to the nearest downgradient Base boundary also are presented in Table 5.1. These target concentrations do not account for any natural chemical or biological processes that could minimize or eliminate contaminant migration or mass. The nature and extent of dissolved contaminant transport in groundwater at the site is quantitatively investigated in Section 6.6.3 using the Bioplume II model code.

5.2.2 Promulgated Remedial Goals for Contaminated Soils and Groundwater

Another source of remedial action goals for contaminated media are applicable or relevant and appropriate requirements, rules, criteria, limitations, and standards of state and federal environmental law. These standards may be used as a basis for establishing desired cleanup levels based on either legally enforceable federal and state requirements

TABLE 5.1
SUMMARY OF CHEMICAL-SPECIFIC REMEDIAL GOALS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

	Onsite Construction Worker Health-Based[a/]			Crossmedia Impacts Leaching from Soils[b/]		
Compound	10^{-6} risk level[c/]	10^{-4} risk level[d/]	HQ = 1[e/]	10^{-6} risk level	10^{-4} risk level	HQ = 1
Soil (mg/kg)						
Benzene	35	3,549	-----	0.08	8	-----
Toluene	-----	-----	18,043	-----	-----	123
Ethylbenzene	-----	-----	13,062	-----	-----	53
Xylenes	-----	-----	294,185	-----	-----	1,365
Naphthalene	-----	-----	-----	-----	-----	413
Groundwater (µg/L)						
Benzene	281.30	28,130	-----			
Toluene	-----	-----	233,078			
Ethylbenzene	-----	-----	116,539			
Xylenes	-----	-----	2,330,779			
Naphthalene	-----	-----	46,616			

[a/] Health-based cleanup criteria are calculated to define the concentration of contaminant that can remain in onsite media and not pose an unacceptable carcinogenic or noncarcinogenic health risk to onsite workers. Soil cleanup criteria are calculated to be the concentration that would prevent potential health risks due to incidental ingestion of contaminated particles, inhalation of volatizing chemicals, and dermal contact using site-specific exposure assumptions. Groundwater cleanup criteria are calculated to be the concentration that would prevent potential health risks due to incidental dermal contact using site-specific exposure assumptions. See Appendix G for details on the derivation of these site-specific risk-based criteria.

[b/] Risk-based criteria calculated to define the concentration of contaminant that can remain in soils and not pose a risk to groundwater quality. Target soil criteria are sufficient to prevent contaminants from leaching at concentrations greater than the health-based groundwater cleanup criteria. See Appendix G for details on how the Summers Model was used to establish the soil concentrations that prevent unacceptable groundwater quality impacts.

[c/] Target risk level used to calculate risk-based criteria that represents a one-in-one-million excess cancer risk due to exposure to a carcinogen. Commonly known as point of departure.

[d/] Target risk level used to calculate risk-based criteria that represents a one-in-ten thousand excess cancer risk due to exposure to a carcinogen. Upper bound target risk level which triggers the need for remedial action per NCP and EPA risk guidance.

[e/] Target hazard quotient used to calculate risk-based criteria that represents no adverse health risk due to exposure to a single noncarcinogen. No attempt was made to define target concentrations for noncarcinogens given the presence of multiple substances.

or federal and state standards, criteria, or limitations that, while not legal requirements, are designed to address problems similar to those encountered at the site. Although this RAP is designed to develop an appropriate risk-based remediation plan for Area D, a review of potential chemical-specific federal and state standards was conducted. Potential chemical-specific remediation goals include the following:

- National Primary Drinking Water Standards - MCLs [Title 40, Code of Federal Regulations Part 141 (40 CFR 141)];
- Secondary Drinking Water Standards - Secondary MCLs [40 CFR 143];
- Maximum Contaminant Level Goals (MCLGs) for Drinking Water [40 CFR 141];
- Remediation Criteria for Petroleum-Contaminated Soils [ARSD Chapter 74:03:32}; and
- Groundwater Quality Standards [ARSD Chapter 74:03:15]

The Ground Water Protection Standards of the Resource Conservation and Recovery Act (RCRA) (40 CFR 264.94, Subpart F) were not considered to be potential target criteria because none of the COPCs for Area D are regulated under these standards. No promulgated standards for the soil COPCs (i.e., the BTEX compounds) were identified.

The shallow groundwater underlying Area D is not now used and is not planned to be used as a drinking water source. However, the shallow groundwater is within a formation which serves as a drinking water source and is in hydraulic communication with groundwater used as a drinking water source at off-Base locations. Thus, the primary MCLs were determined to be relevant and appropriate for areas downgradient of Area D because the shallow groundwater in areas beyond Base control is used to support current drinking water supplies. MCLs and non-zero MCLGs are to be attained by remedial actions for groundwater or surface waters that are current or potential sources of drinking water [see 40 CFR 430(e)(2)(i)(B)]. However, the preamble to the National Contingency Plan (NCP) states that MCLs are usually only legally applicable under the Safe Drinking Water Act (SDWA) to the quality of drinking water at the tap. This means that there will be few instances in which MCLs are legally applicable target criteria for the restoration of groundwater in place (55 FR No. 46, March 8, 1990).

The MCLG value for benzene is zero. The NCP states that where the MCLG for a contaminant has been set at a level of zero, the MCL promulgated for that contaminant under the SDWA shall be attained for groundwaters that are current or potential sources of drinking water [40 CFR 300.430(e)(2)(i)(C)]. Therefore, the MCL of 5 μg/L was selected as the promulgated standard for benzene. Note that the risk-based remedial goal for benzene is less stringent than the primary MCL. No primary MCL for naphthalene has been developed by EPA. There were no secondary MCLs identified for either benzene or naphthalene.

SDDENR has promulgated state groundwater quality standards for both benzene and naphthalene. These standards are defined as the allowable concentration in groundwater at any place of groundwater withdrawal (ASDR Chapter 74:03:15:03). The State has adopted the primary MCL for benzene as the state groundwater quality standard. In the absence of a federal MCL, the State has defined naphthalene as a "potential toxic pollutant" (ASDR Chapter 74:03:15:04). The state groundwater quality standard for all "potential toxic pollutants" has been defined as the detection limit of the analytical technique. Table 2.1 specifies that the detection limit for naphthalene in groundwater achieved under this project is 10 µg/L. Therefore, 10 µg/L has been included on Table 5.1 as the promulgated groundwater quality standard for naphthalene.

5.3 REMEDIATION REQUIREMENTS

Table 5.1 summarizes the relevant risk-based remedial goals developed to be protective of human health and the environment and other chemical-specific standards for each of the COPCs in soil and groundwater at Area D. The risk-based remedial goals are the most appropriate cleanup levels to provide the desired level of risk reduction for potential onsite and downgradient receptors. The degree of cleanup implied by the promulgated standards is more than is necessary to protect human health and the environment given current and foreseeable exposure potential. Imposing compliance with primary MCLs for groundwater at this site would directly conflict with a risk-based approach to remediation, and is not required for sites seeking classification under the inactive status category (SDDENR, 1994).

Table 5.2 identifies, by environmental medium, the Area D COPCs that were measured during either the 1991/1992 or 1994 field efforts at concentrations in excess of concentrations required to provide the desired level of risk reduction at and downgradient of the site. Benzene in soils and groundwater is the only COPC to exceed the most stringent risk-based remedial goal. Benzene in groundwater also exceeds the MCL of 5 µg/L. Benzene was measured in soils in 1993 and 1994 at concentrations slightly above the risk-based remedial goal calculated to protect groundwater quality from adverse impacts due to contaminants leaching from soils. Benzene was measured in groundwater in both 1991/1992 and 1994 at concentrations above both the most stringent risk-based remedial goal and its primary MCL. Although naphthalene was detected in groundwater in 1994 at concentrations above the analytical detection limit, naphthalene was not measured in groundwater at concentrations above the most stringent risk-based remedial goal.

Therefore, only benzene in both soils and groundwater qualifies as the site-specific remediation target chemical or chemical of concern (COC) that needs to be addressed during the remedial action. Note that naphthalene does not strictly qualify as a COC for groundwater at the site because it was not measured at concentrations above the target risk-based goals for the site. None of the other BTEX compounds were measured in groundwater at concentrations equal to or above risk-based or promulgated remedial goals. However, to verify that no site-related contamination will migrate to the downgradient Base boundaries at concentrations above state groundwater quality standards, all BTEX compounds and naphthalene were considered in the quantitative chemical fate analysis in Section 6. This approach will also account for the total mass of dissolved COCs that can be biodegraded in groundwater over time.

TABLE 5.2
COMPARISON OF COPC CONCENTRATIONS TO CHEMICAL-SPECIFIC REMEDIAL GOALS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

	1991/1992 Fuel Spill Survey	1993 Initial Bioventing Results	1994 1-Year Bioventing Results	1994 Risk-Based Remediation	Site-Specific Risk Based Criteria Onsite Workers			Groundwater Impact via Leaching From Soil		
COPC (units)	MaximumConcentration	MaximumConcentration	MaximumConcentration	MaximumConcentration	10^{-6} risk level	10^{-4} risk level	HQ = 1	10^{-6} risk level	10^{-4} risk level	HQ = 1
Soil										
Benzene (mg/kg)	0.4	15	0.19	1.1	35	3,549	--	0.08	8	--
Toluene (mg/kg)	17	13	0.063 U	4.1	--	--	18,043	--	--	123
Ethylbenzene (mg/kg)	15	53	3.7	2	--	--	13,062	--	--	53
Total xylenes (mg/kg)	81	310	21	74	--	--	294,185	--	--	1,365
Groundwater										
Benzene (µg/L)	2,675	--	--	3,400	281	28,130	--	--	--	--
Naphthalene (µg/L)	--	--	--	300	--	--	46,616	--	--	--

NOTE: Shading indicates concentration exceeds contaminant screening criterion. Both concentration and exceeded criterion are shaded.

SECTION 6

EVALUATION OF INTRINSIC REMEDIATION

6.1 INTRODUCTION

Section 3 of this RAP is devoted to describing the physical site conditions at Area D. Section 4 summarizes the nature and extent of site-related contamination. Section 5 of the RAP describes the proposed site-specific cleanup criteria for impacted media to protect human health and the environment. Section 5 also identifies the COCs for the site that must be addressed by remedial activities to assure that the site may be eligible for inactive status classification. This section documents what effect natural attenuation processes have had and will have on the extent of migration, mass, persistence, and toxicity of naphthalene and each of the BTEX compounds. This section summarizes and interprets site characterization data used to document the effectiveness of natural chemical, physical, and biological processes which can minimize naphthalene and BTEX migration and reduce contaminant mass over time and distance.

Although benzene is the only COC for Area D, all of the contaminants (BTEX and naphthalene) were considered in this quantitative evaluation for two primary reasons. First, the screening exposure pathway analysis completed in Section 5 indicated that exposure pathways to offsite receptors may be completed in approximately 70 years if site-related contaminants migrated at hazardous concentrations to potential offsite exposure points. Consequently, the quantitative chemical fate assessment was scoped to include all COPCs for Area D. The objective of this evaluation was to quantitatively determine whether any exposure pathways involving offsite receptors could reasonably be completed when the effects of natural chemical attenuation processes were considered. In the event that this analysis indicates that an offsite exposure pathway could be completed, exposure-point concentrations would have to be compared to appropriate health-protective target concentrations to assess the need for additional remediation to achieve the desired level of risk reduction at the site. The risk-based remedial goals developed in Section 5 were calculated to protect onsite workers engaged in normal and possibly deep excavation activities against unacceptable risks due to exposure to impacted media, and do not represent appropriate remedial goals for groundwater used as a potable water source.

Second, the beneficial impact of natural chemical destructive attenuation processes depends on the total mass of hydrocarbons in saturated media at the site. If the fate of benzene was evaluated exclusive of other BTEX compounds or naphthalene, the impacts of chemical attenuation processes may be overestimated. To provide a conservative estimate of the effects of these processes on mass, concentration, mobility, persistence, and toxicity, all of the COPCs were factored into the analysis.

6.2 OPERATIVE MECHANISMS OF CONTAMINANT ATTENUATION

Understanding the fate of naphthalene and each of the BTEX compounds in environmental media is critical to evaluating and predicting contaminant distribution patterns. There are several physical, chemical, and biological processes that influence how a chemical behaves in soil and groundwater. The following sections present a brief overview of the major chemical characteristics that define the fate of JP-4 jet fuel constituents in soils and groundwater at Area D. These chemical characteristics ultimately determine if the mass of contaminants in the environment can be eliminated or rendered immobile by natural processes. The positive effects of these natural processes on reducing the actual mass of naphthalene and BTEX and/or minimizing the extent of migration in groundwater and soil is termed intrinsic remediation.

6.2.1 Contaminant Characteristics and Mass Transport Mechanisms

The relative solubility, sorptive nature, and volatility of a chemical can govern the effectiveness of nondestructive chemical attenuation processes at Area D. Nondestructive attenuation processes can be described as those physical and chemical processes that may prohibit significant contaminant migration but may not result in a permanent reduction in contaminant mass. Examples of nondestructive attenuation processes include volatilization, sorption, advection, and dispersion. These processes must be evaluated when determining whether a compound poses an actual risk to human health and the environment. If the contaminant is not likely to reach a potential receptor, the contaminant poses no risk.

6.2.1.1 Solubility

The water solubility of a chemical species defines how that particular chemical could partition (leach) from a contaminant source and dissolve into and migrate with groundwater. In general lighter hydrocarbon chains tend to be more water soluble than heavier hydrocarbon chains. For example, the water solubilities of benzene, toluene, ethylbenzene, the various xylene isomers, and naphthalene are above 1,700 milligrams per liter (mg/L), 500 mg/L, about 160 mg/L, and about 145 to 175 mg/L, and 30 mg/L respectively (Bohon and Claussen, 1951; Mackay and Shiu, 1981; Verschueren, 1983; Isnard and Lambert, 1988; Howard, 1990). Consequently, even though naphthalene and the BTEX compounds may comprise a low mass fraction (i.e., approximately 4 percent) of the initial source of contamination, these compounds preferentially leach from contaminated soil or dissolve from free product into groundwater and migrate as dissolved contamination (Lyman *et al.,* 1992).

Dissolution of soluble contaminants from residual soil contamination and LNAPL can be a significant source of groundwater contamination. Both of these potential sources of contamination were retained for more detailed evaluation as part of the screening exposure pathway analysis completed in Section 5. The potential impacts of contaminants leaching from soils and impacting groundwater quality are quantitatively evaluated in Section 6.6.1. Previous site investigations have also documented the presence of variable thicknesses of LNAPL at the site. In 1994 and 1995, measurable thicknesses of LNAPL were only encountered at MW-6. Previous investigations documented the presence of residual or mobile LNAPL in MW-4, but this well had collapsed prior to the 1994 field investigation and could not be sampled. Although dissolved concentrations of BTEX and naphthalene measured in groundwater collected beneath the thin layer of LNAPL at MW-6 were similar to concentrations measured in groundwater samples collected from MW-40 and MW-39, no LNAPL has ever been encountered in the latter two wells. The effects of dissolution of soluble contaminants from LNAPL on groundwater quality is quantitatively evaluated in Sections 6.6.2 and 6.6.3.

6.2.1.2 Sorption

Another chemical characteristic that can govern how a compound is attenuated in soil and groundwater is its sorptive properties. If a contaminant can be strongly sorbed to the aquifer matrix, the compound will be less mobile and less likely to be transported great distances from the source area. The BTEX compounds are less sorptive than other petroleum hydrocarbons. Naphthalene tends to sorb more strongly than the BTEX compounds. Benzene does not sorb readily to soil and is considered the most mobile of the BTEX compounds. Toluene sorbs more readily to soil than benzene, but is still very mobile. Ethylbenzene sorbs more strongly to soil than benzene but less strongly than toluene. Of all the BTEX compounds, xylenes sorb most strongly to soil, but can still leach from unsaturated soil and dissolve and migrate slowly in groundwater (Abdul *et al.,* 1987). In comparison, heavier hydrocarbons such as naphthalene sorb more strongly to the soil matrix and migration is limited in both soil and groundwater (Verschueren, 1983).

The total organic carbon (TOC) content of both unsaturated and saturated soils was measured as part of the 1994 field test. The total organic carbon content ranged from less than 0.42 percent to 1.1 percent (Appendix A). The measured background concentration of total organic carbon in soils was determined to be about 0.42 percent at MW-26. Hydrocarbons, including naphthalene and the BTEX compounds, sorb primarily to that portion of the soil matrix that is composed of organic carbon. Thus, less than 0.0042 kg of organic carbon per kg of soil is available to sorb contaminants. This level of organic carbon is not likely to significantly retard chemicals, but is sufficient to slow contaminant leaching and migration. The effects of sorption tend to be more pronounced with increases in molecular weight and complexity. Thus, sorptive effects should be most pronounced for naphthalene and least pronounced for benzene. Toluene, ethylbenzene, and xylenes should have sorptive properties somewhere in between these two extremes. The effect of sorption on leaching from unsaturated and saturated soils into groundwater and contaminant velocity in groundwater is described in subsequent sections.

6.2.1.3 Volatility

The volatility of naphthalene and each of the BTEX compounds also affects how the contaminants behave in the environment. All of the BTEX compounds are classified as volatile chemicals because they have vapor pressures in excess of 0.1 millimeter of mercury (mm Hg). Benzene is the most volatile of the BTEX compounds, with a vapor pressure of about 95 mm Hg, and xylenes are the least volatile with vapor pressures between 6 and 9 mm Hg. The PAH compound naphthalene is not considered a volatile chemical. Naphthalene has a vapor pressure below 0.1 mm Hg.

Volatilization from contaminated media was investigated as a mass transport mechanism at Area D. The soil flux concentration of the BTEX and petroleum hydrocarbon compounds were measured at the site (Appendix A, Table A.3 and Table A.4). These analytical data imply that the depth from the ground surface to soil contamination and the clayey nature of the vadose soils present at Area D have minimized the importance of volitilization at the site. Only low concentrations of each of the BTEX compounds were detected in the soil flux samples collected at the site. The risk-based remediation criteria for soils were calculated to protect onsite workers from health risks associated with exposure to soils during both normal and deep excavation activities. The soil concentration goals include volatilization of contaminants from exposed soils. Benzene was the only compound in soils to exceed a risk-based remediation criterion for soils (i.e., the criterion calculated to prevent adverse impacts to groundwater quality due to leaching from contaminated soils). Soil concentrations of benzene were below the health-protective concentrations calculated to protect against unacceptable risks due to direct contact, inhalation, and incidental ingestion (Table 5.2). Because no significant soil flux was measured at the site and because concentrations of volatile contaminants are below the health-protective criteria developed using reasonable, site-specific exposure assumptions, the volatilization pathway is not a major risk element and is not significantly involved in chemical fate at the site.

6.2.1.4 Discussion

The preceding discussion shows that solubility and sorptive characteristics are important chemical characteristics to consider when assessing whether hydrocarbon contamination in soil and groundwater at Area D may present an unacceptable risk to human health and the environment. Site contaminants characterized by relatively high water solubility and low sorptive properties, such as the BTEX compounds and to a lesser extent naphthalene, can be rapidly introduced into and transported with groundwater. Consequently, because naphthalene and the BTEX compounds are relatively mobile, they may drive the type and magnitude of remediation necessary to isolate the contamination and protect downgradient receptors from potential risks due to exposure to these chemicals. Typically, naphthalene is less soluble than the BTEX compounds and is more effectively sorbed to the soil matrix. Thus, it is slightly less mobile than the BTEX compounds and is more likely to be isolated in and near the initial source of contamination.

6.2.2 Biodegradation of BTEX Compounds in Soil and Groundwater

Biodegradation may also act as a chemical attenuation process. In comparison to nondestructive chemical attenuation processes, destructive chemical attenuation processes result in the permanent removal of contaminant mass from the environment and may reduce the length of time required to attain cleanup goals. Documenting and distinguishing the effects of destructive attenuation processes, such as biodegradation, from nondestructive attenuation processes is critical to evaluating the potential for intrinsic remediation to bring about a reduction in contaminant mass over time. The effectiveness of destructive attenuation processes at reducing contaminant mass at a site depends on how amenable the chemical is to biodegradation and whether the site is characterized by physical, chemical, and biological conditions favorable to such processes.

Numerous laboratory and field studies have shown that hydrocarbon-degrading bacteria can participate in the degradation of many of the chemical components of JP-4 jet fuel, including the BTEX compounds and the PAHs, under both aerobic and anaerobic conditions (e.g., Jobson *et al.,* 1972; Perry, 1977; Atlas, 1981, 1984, 1988; Gibson, 1984; Reinhard *et al.,* 1984; Young, 1984; Bartha, 1986; Wilson *et al.,* 1986, 1987, 1990; Baedecker *et al.,* 1988; Lee, 1988; Chiang *et al.,* 1989; Grbic-Galic, 1989, 1990; Leahy and Colwell, 1990; Parker *et al.,* 1990; Stieber *et al.,* 1990, 1994; Altenschmidt and Fuchs, 1991; Alvarez and Vogel, 1991; Baedecker and Cozzarelli, 1991; Bauman, 1991; Borden, 1991; Brown and McFarland, 1991; Haag *et al.,* 1991; Hutchins and Wilson, 1991; Beller *et al.,* 1992; Bouwer, 1992; Edwards and Grbic-Galic, 1992; Thierrin *et al.,* 1992; Malone *et al.,* 1993; Davis *et al.,* 1994; ES, 1994a Parsons ES, 1994b, 1994c, 1995). Biodegradation of fuel hydrocarbons will occur when an indigenous population of hydrocarbon-degrading microorganisms is present in the soil and groundwater, and sufficient concentrations of electron acceptors and nutrients, including fuel hydrocarbons, are available to these organisms. Soils and groundwater with a history of exposure to BTEX and PAH compounds generally contain microbial populations competent to facilitate biodegradation reactions (Zobell, 1946; Litchfield and Clark, 1973; Borden, 1994; Seech *et al.,* 1994; Simpkin and Giesbrecht, 1994). The chemical basis for the biodegradation of BTEX compounds is described in more detail in Section 6.4, where geochemical data relevant to documenting biodegradation at the field scale at Area D are presented.

6.3 EVIDENCE OF FIELD-SCALE CONTAMINANT MASS LOSS

The first step in determining whether site data indicate that BTEX compounds are biodegrading in groundwater at Area D is to evaluate the analytical data presented in Section 4. Comparison of analytical data collected in 1991/1992, 1993, and 1994 can be a valuable indicator that contaminants are being destructively attenuated in soil and groundwater at Area D. Site-specific biodegradation rates can also be estimated by examining plume conditions over time and concentration gradients observed at the site.

6.3.1 Observed Changes in COC Concentration in Soils

The 1994 field investigation results indicate that soils are contaminated with residual concentrations of fuel hydrocarbon constituents (Section 4). As described in Section 5, detected concentrations of BTEX were measured in 27 of the 48 unsaturated and saturated soil samples collected at the site during the 1991/1992, 1993, and 1994 field investigations. All of these soil samples were collected from the suspected source area (i.e., 21 samples) or immediately downgradient from the suspected source area (i.e., 6 samples). Although concentrations of each of the BTEX compounds were measured in soil samples above screening level criteria (Section 4), only benzene was present at concentrations above a site-specific remedial criterion (Section 5).

Similar concentrations of total BTEX in soil samples were collected within the suspected source area in 1991/1992 and 1994. For example, total BTEX in soil collected at a depth of 4 to 6 feet bgs at BH-7 in 1991/1992 was 98.4 mg/kg. In comparison, total BTEX in soil collected at a depth of 13.5 to 14.5 feet bgs at MW-40, which is about 47 feet southwest of BH-7, in 1994 was 90.3 mg/kg. Additionally, total BTEX was measured in soil collected at a depth of 20 to 22.5 feet bgs at BH-8 in 1991/1992 was 45.8 mg/kg. Total BTEX measured in soil collected at a depth of 21.5 to 22.5 feet bgs at MW-36, which is about 38 feet north of BH-8, in 1994 was 12.5 mg/kg.

Although it is difficult to compare single-point concentration results for soil samples due to the heterogeneity of the environmental media, these analytical results suggest that, with the exception of the bioventing pilot test area, soil concentrations have not markedly decreased from 1991/1992 to 1994. Although the BTEX compounds are highly soluble, these compounds do not appear to be rapidly partitioning from soils over time. The lack of natural contaminant mass removal from soils at Area D suggests that these constitutents are effectively occluded in soils and are not naturally degrading. Additionally, the low levels of precipitation infiltration and the presence of the shallow clayey layer may reduce vertical contaminant transport at the site. Site data suggest that even soluble contaminants are not rapidly partitioning from soils and dissolving into groundwater. The significance of this release mechanism (leaching) is quantitatively evaluated in Section 6.6.1 using site-specific data. Additionally, low soil gas oxygen concentrations measured as part of the bioventing pilot test (Sections 4 and 7) indicated that natural *in situ* biodegradation of fuel hydrocarbons could not proceed at appreciable rates without the addition of oxygen into the subsurface. The beneficial effects of bioventing source area soils at Area D is described in Section 7.

These may be important considerations when estimating the potential risk associated with contaminated soils at the site. If contaminants are not leaching from soils to impact groundwater quality, and concentrations do not present a risk to onsite workers due to direct contact, inhalation, and/or incidential ingestion, there may be no need to remediate soils to protect human health and the environment. However, the absence of these processes also means that appreciable *in situ* reductions of contaminant mass in soils over time are not likely to be realized without some type of active remediation. The site-specific *in situ* contaminant reductions that can be achieved in soils as a result of implementing full-scale bioventing is fully summarized in Section 7.

6.3.2 Observed Changes in COC Concentrations in Groundwater

During the 1991/1992 sampling event (FMG, 1991 and 1992), the maximum concentration of benzene detected in groundwater was 2,675 µg/L at MW-20. In comparison, the maximum concentration of benzene detected at Area D in 1994 was 3,400 µg/L at MW-39, which is about 170 feet upgradient from MW-20. The measured concentration of benzene at MW-6, which is located approximately 100 feet upgradient from MW-20, was 2,000 µg/L. All of these wells are located in the suspected source area. From these data, it appears that the 1991/1992 sampling event did not completely define the areal extent of the suspected source area. The 1994 sampling results suggest that elevated concentrations of dissolved benzene are present as far upgradient as MW-40 and as far downgradient as MW-29 (Figure 4.2). Analytical data collected from monitoring wells in 1994 confirmed the lateral extent of the dissolved plume defined in 1991/1992.

Analytical data collected from the closest two wells (MW-20 and MW-6) indicate a slight reduction in benzene concentration in groundwater in the source area between the 1991/1992 and 1994 sampling events. Even though LNAPL was encountered in MW-20 in 1991/1992 and in MW-6 in 1994, the concentration of dissolved benzene at these neighboring sampling locations decreased slightly from 2,675 µg/L to 2,000 µg/L between January 1992 and October 1994. The absence of significant decreases in observed concentrations of dissolved benzene within the suspected source area over time indicates that contaminated soils and/or the isolated pocket of LNAPL are still present in this area or that significant contaminant migration or degradation is not occurring.

6.3.3 Observed Changes in Extent of Dissolved Plume

In addition to slight reductions in contaminant mass over time at the site, it is possible that minimal plume migration has occurred since the 1991/1992 sampling event. The maximum extent of dissolved benzene contamination in 1991/1992 was estimated to be about 350 feet downgradient from the suspected source area. This estimate was based on the analytical results from MW-4 and MW-23. No BTEX was detected at MW-23 during the 1991/1992 sampling event, which suggested that no dissolved contamination had migrated to MW-23. In comparison, the total extent of detected concentrations of benzene in groundwater in 1994 was about 530 feet downgradient from the suspected source area. However, analytical data collected in 1994 at MW-23 confirmed the absence of any detected concentration of BTEX at this sampling location. The extent of the dissolved plume appears to have increased, because all of the BTEX compounds were detected in 1994 at MW-29, which is located about 135 feet southeast of MW-23.

The difference in the extent of dissolved contamination between the 1991/1992 and 1994 sampling events may be due to incomplete delineation of the plume during early investigations. As described in previous sections, preferential channels are believed to be present at the site. Site characterization data collected as part of the 1994 field investigation shows a thicker gravel unit running through the source area, through MW-17, and toward MW-29. The gravel unit near MW-23 is not as thick as that found immediately to the southeast and east (Section 4). This gravel unit acts as a preferential conduit. No groundwater samples were collected in 1991/1992 in the vicinity of this apparent channel. Consequently, a realistic estimate of the actual extent of plume migration that occurred between January 1992 and October 1994 cannot be identified because the areal extent of dissolved contamination in January 1992 was underestimated.

6.3.4 Estimating Site-Specific Contaminant Biodegradation Rates for Saturated Media

It is important to distinguish between the effects of nondestructive attenuation processes such as advection, dispersion, and sorption and the effects of destructive attenuation processes such as biodegradation on the mass of dissolved contaminants in the groundwater at Area D. To quantify these effects, a spatial regression technique (Buscheck and Alcantar, 1995) was used to estimate the site-specific biodegradation rates of each of the contaminants in saturated soil and groundwater based on analytical data.

It is commonly assumed that biodegradation rates for fuel hydrocarbon compounds in saturated media can be approximated by a first-order decay constant. The rates of biodegradation of both BTEX and PAH compounds can be calculated and compared in this manner because the biodegradation processes for each is similar (Chapelle, 1993). A spatial regression analysis of contaminant concentration data is presented in Appendix E. The slope of the best fit regression line through measured concentrations versus distance is used to estimate the amount of distance that naphthalene and each of the BTEX compounds was attenuated that cannot be explained by advection, dispersion, and sorption (Buscheck and Alcantar, 1995). This spatial regression technique is more clearly described in Appendix E.

Table 6.1 summarizes the calculated biodegradation rates for total BTEX, benzene, toluene, ethylbenzene, total xylenes and naphthalene based on analytical data collected at Area D. These rates express how much of the contaminant mass is being removed from the saturated media that cannot be explained by nondestructive chemical attenuation processes such as dispersion and sorption. The effects of both aerobic and anaerobic destructive attenuation processes are included in these site-specific biodegradation rate constant estimates. The rates calculated for Area D should be considered conservative estimates. The potential for a continuing fuel leak at the site, which will add additional contaminant mass to the groundwater, was not factored into the rate estimates. This additional contaminant mass would mask the apparent effectiveness of biodegradation processes at the site.

The calculated biodegradation rate for total BTEX compounds in saturated soil and groundwater at Area D is 0.00115 day^{-1}, which compares favorably to the saturated soil and groundwater degradation rates for benzene, toluene, ethylbenzene, and total xylenes found in the technical literature. The site specific biodegradation rate of benzene was calculated to be 0.00107 day^{-1}, slightly less than that of total BTEX. This is expected, as benzene is known to be more recalcitrant to biological degradation than the other BTEX compounds (Chapelle, 1993). Reported literature values of biodegradation rates for benzene in saturated soils and groundwater range from 0.0009 day^{-1} to 0.069 day^{-1} (Howard *et al.,* 1991). The site-specific biodegradation rate for benzene falls within this literature range of biodegradation rates.

Literature biodegradation rates for toluene are generally faster than benzene, ranging from 0.025 day^{-1} to 0.098 day^{-1} (Howard *et al.,* 1991). The site-specific biodegradation rate of toluene in saturated media Area D was estimated to be 0.00125 day^{-1}. This site specific rate is faster than the site-specific biodegradation rate for benzene, but slower than the typical biodegradation rates reported in literature. Literature values of biodegradation rates of ethylbenzene in saturated soils and groundwater are reported from 0.003 day^{-1} to 0.1 day^{-1} (Howard *et al.,* 1991). The site-specific biodegradation rate of ethylbenzene in groundwater at Area D was estimated to be 0.00075 day^{-1}. The site specific rate for biodegradation of ethylbenzene is well below typical literature values of biodegradation rates reported for ethylbenzene. Literature values of biodegradation rates reported for total xylenes in saturated media range from 0.002 day^{-1} to 0.05 day^{-1} (Howard *et al.,* 1991). The site-

TABLE 6.1
COMPOUND-SPECIFIC BIODEGRADATION RATES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Compound	Contaminant Velocity (ft/day)	Site-specific Biodegradation Rate (1/day)[a/]	Literature-reported Biodegradation Rates (1/day)[b/]
Total BTEX	0.230	0.00115	0.0009 - 0.23
Benzene	0.234	0.00107	0.0009 - 0.069
Toluene	0.150	0.00125	0.025 - 0.098
Ethylbenzene	0.168	0.00075	0.003 - 0.1
Total xylenes	0.139	0.00077	0.002 - 0.05
Naphthalene	0.012	0.00007	0.0024 - 0.69

[a/] Rate calculated using method described in Appendix E.

[b/] Based on biodegradation rates reported in Howard *et al.*, 1991 specific biodegradation rate for total xylenes in groundwater was calculated to be 0.00077 day^{-1}. This site-specific rate is well below reported literature values.

Literature values of biodegradation rates for naphthalene in saturated soils and groundwater range from 0.0024 day^{-1} to 0.69 day^{-1} (Howard *et al.,* 1991). The biodegradation rate of naphthalene in site groundwater at Area D was estimated to be 0.00007 day^{-1}. The site specific biodegradation rate for naphthalene is, as expected, much slower than the any of the site-specific biodegradation rates measured for the BTEX compounds. But, the site-specific rate derived from conservative site data also is much slower than the biodegradation rates of naphthalene reported in the technical literature. Based on the calculated biodegradation rates, the site-specific half-lives of total BTEX, benzene, toluene, ethylbenzene, total xylenes, and naphthalene in saturated soil and groundwater at Area D are 1.6, 1.8, 1.5, 2.5, 2.5, and 29 years, respectively.

6.4 EVIDENCE OF CONTAMINANT BIODEGRADATION VIA MICROBIALLY CATALYZED REDOX REACTIONS

Available site data presented in preceding sections suggest that the BTEX compounds and naphthalene are biodegrading in groundwater at Area D. Spatial regression techniques were applied to calculate site-specific biodegradation rates for all of the groundwater contaminants. On the basis of this evaluation, it can be inferred that naphthalene and the BTEX compounds are slowly biodegrading at Area D.

There also is another line of evidence that can be used to show that these contaminants are biodegrading in saturated soil and groundwater at Area D. Analytical data on potential electron acceptors can be used as geochemical indicators of biodegradation (Salanitro, 1993; McCallister and Chiang, 1994; Wiedemeier *et al.,* 1995; Borden *et al.*, 1995). Reductions in the concentrations of oxidized chemical species that are used by microorganisms to facilitate the oxidation of naphthalene and the BTEX compounds is another indication that contaminants are biodegrading. The amount of potential electron acceptors available to participate in contaminant biodegradation reactions can be used to estimate the total contaminant mass that can be biodegraded over time at this site. Coupled with the biodegradation rates described earlier, this information can be used to predict how much and how quickly contaminant mass can be permanently removed from saturated soils and groundwater at Area D by natural processes. These data can also be used to assess whether potentially significant exposure pathways involving offsite receptors could be completed over time.

6.4.1 Relevance of Redox Couples in Biodegradation

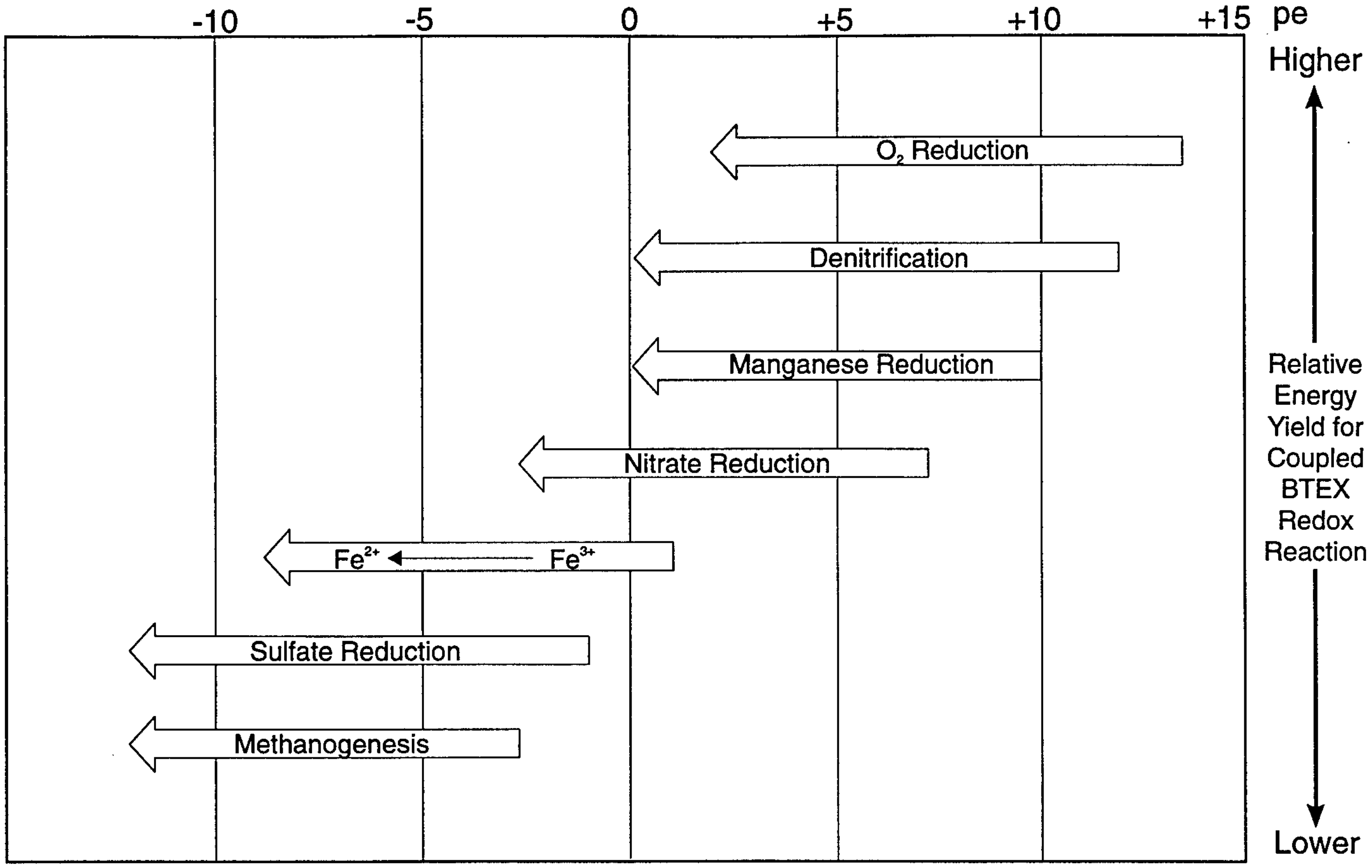
Microorganisms obtain energy to replenish enzymatic systems and to reproduce by oxidizing organic matter. Biodegradation of naphthalene and the BTEX compounds is the result of a series of reduction-oxidation (redox) reactions which maintain the charge balance within the natural environment. Microorganisms facilitate the degradation of naphthalene and the BTEX compounds by transferring electrons from the contaminants (electron donor) to available electron acceptors. Electron acceptors are elements or compounds that occur in relatively oxidized states and can participate in redox reactions involving naphthalene and the BTEX compounds. Electron acceptors that may be present in saturated soil and groundwater at Area D are oxygen, nitrate, manganese, sulfate, ferric iron, and carbon dioxide.

Microorganisms facilitate naphthalene and BTEX biodegradation to produce energy for their use. The amount of energy that can be released when a reaction occurs or is required to drive the reaction to completion is quantified by the free energy of the reaction (Stumm and Morgan, 1981; Bouwer, 1994; Chapelle, 1993; Godsey, 1994; Mueller *et al.,* 1994; Berg *et al.,* 1994). Microorganisms will facilitate only those redox reactions that will yield energy. Microorganisms are able to utilize electron transport systems and chemiosmosis to combine energetically favorable and unfavorable reactions to produce energy for life processes. By coupling the oxidation of naphthalene and the BTEX compounds, which requires energy, to the reduction of other compounds (e.g., oxygen, nitrate, manganese, ferric iron, sulfate, and carbon dioxide), which yield energy, the overall reaction will yield energy. Detailed information on the redox reactions required to biodegrade naphthalene and each of the BTEX compounds is included in Appendix E. The reader is encouraged to review this information to more fully understand the chemical basis of biodegradation.

Figure 6.1 illustrates the sequence of microbially mediated redox processes based on the amount of free energy released for microbial use. In general, reactions yielding more energy tend to take precedence over processes that yield less energy (Stumm and Morgan, 1981; Godsey, 1994; Reinhard, 1994). As Figure 6.1 shows, oxygen reduction would be expected to occur in an aerobic environment with microorganisms capable of aerobic respiration because oxygen reduction yields significant energy (Bouwer, 1992; Chapelle, 1993). However, once the available oxygen is depleted and anaerobic conditions dominate the interior regions of the contaminant plume, anaerobic microorganisms can utilize other electron acceptors in the following order of preference: nitrate, manganese, ferric iron, sulfate, and finally carbon dioxide. Each successive redox reaction provides less energy to the system, and each step down in redox energy yield would have to be paralleled by an ecological succession of microorganisms capable of facilitating the pertinent redox reactions.

The expected sequence of redox processes is also a function of the oxidizing potential (Eh) of the groundwater. The oxidizing potential measures the relative tendency of a solution or chemical reaction to accept or transfer electrons. The oxidizing potential of the groundwater can be measured in the field. This measurement can be used as an indicator of which redox reactions may be operating at a site. This field measurement can then be expressed as pe, which is the hypothetical measure of the electron activity associated with a specific Eh. High pe means that the solution or redox couple has a relatively high oxidizing potential.

Microorganisms can only facilitate the biodegradation (oxidation) of naphthalene and BTEX compounds using redox couples that have a higher oxidizing potential than the contaminants. Appendix E includes tables that show that redox couples including nitrate, oxygen, manganese, ferric iron, sulfate, and carbon dioxide all have higher oxidizing potentials than the redox couples including naphthalene and BTEX compounds. This is why these electron acceptors can be used to oxidize naphthalene and BTEX compounds. The reduction of highly oxidized species results in an overall decrease in the oxidizing



Notes

1. These reactions would be expected to occur in sequence if the system is moving toward equilibrium.

2. These redox processes occur in order of their energy-yielding potential (provided microorganisms are available to mediate a specific reaction). Reduction of a highly oxidized species decreases the pe of the system.

3. The pe of the system determines which electron acceptors are available for COC oxidation.

4. Redox sequence is paralleled by an ecological succession of biological mediators.

Adapted from Stumm and Morgan, 1981.

FIGURE 6.1

SEQUENCE OF MICROBIALLY MEDIATED REDOX PROCESSES

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potential of the groundwater. As shown in Figure 6.1, the reduction of oxygen and nitrate will reduce the oxidizing potential to levels at which manganese and ferric iron (Fe^{3+}) reduction can occur. As each chemical species that can be used to oxidize the contaminants is exhausted, the microorganisms are forced to use other available electron acceptors with lower oxidizing capacity. When sufficiently negative pe levels have been developed as a result of these redox reactions, sulfate reduction and methanogenesis can occur almost simultaneously (Stumm and Morgan, 1981).

6.4.2 Dissolved Oxygen Concentrations

Almost all types of fuel hydrocarbons can be biodegraded under aerobic conditions (Borden, 1994). Mineralization of fuel hydrocarbons to carbon dioxide and water under aerobic conditions involves the use of oxygen as a cosubstrate during the initial stages of metabolism, and as a terminal electron acceptor during the later stages of metabolism for energy production (Higgins and Gilbert, 1978; Gibson and Subramanian, 1984; Young, 1984). The reduction of molecular oxygen during the oxidation of naphthalene and BTEX compounds yields a significant amount of free energy to the system that the microorganisms can utilize.

Dissolved oxygen (DO) concentrations were measured at groundwater monitoring wells in October 1994. Figure 6.2 presents analytical results for DO by sampling location. The isoconcentration contours compared in Figure 6.2 show that there is a strong correlation between areas of elevated naphthalene and BTEX concentrations and areas depleted of DO relative to measured background levels. DO concentrations from sampling locations within the suspected source area and immediately downgradient from the suspected source area ranged from about 2.5 mg/L to below 0.2 mg/L. In comparison, background concentrations of DO at this site were at least as high as 6.2 mg/L, as indicated by DO concentrations measured in MW-19, and averaged about 5.5 mg/L (as calculated from DO measured in MW-16, MW-19 and MW-32). These locations are upgradient from and outside the area of fuel contamination. DO concentrations at sampling locations downgradient from and/or beyond the area of fuel contamination ranged from 6.4 mg/L (MW-13) to 8.65 mg/L (MW-27). The low concentrations of DO in contaminated groundwater indicate that oxygen is functioning as an electron acceptor during microbially-mediated degradation of fuel hydrocarbons. Use of this electron acceptor during microbial degradation of naphthalene and BTEX compounds is consistent with the measured Eh (pe) levels at the site (Figure 6.1 and Appendix E). However, the reduction of dissolved oxygen concentrations will cause anaerobic conditions, reduce the oxidizing potential of the aquifer, and will bring about a change in the types of microorganisms that facilitate the continued degradation of the contaminants.

6.4.3 Dissolved Nitrate and Nitrite Concentrations

Once anaerobic conditions prevail in the groundwater, nitrate can be used as an electron acceptor by facultative anaerobic microorganisms to mineralize naphthalene and BTEX compounds via either denitrification or nitrate reduction processes. Denitrification is the most energetically favorable of the redox reactions likely to be involved in the oxidation of the contaminants (Appendix E). Although the oxidation of

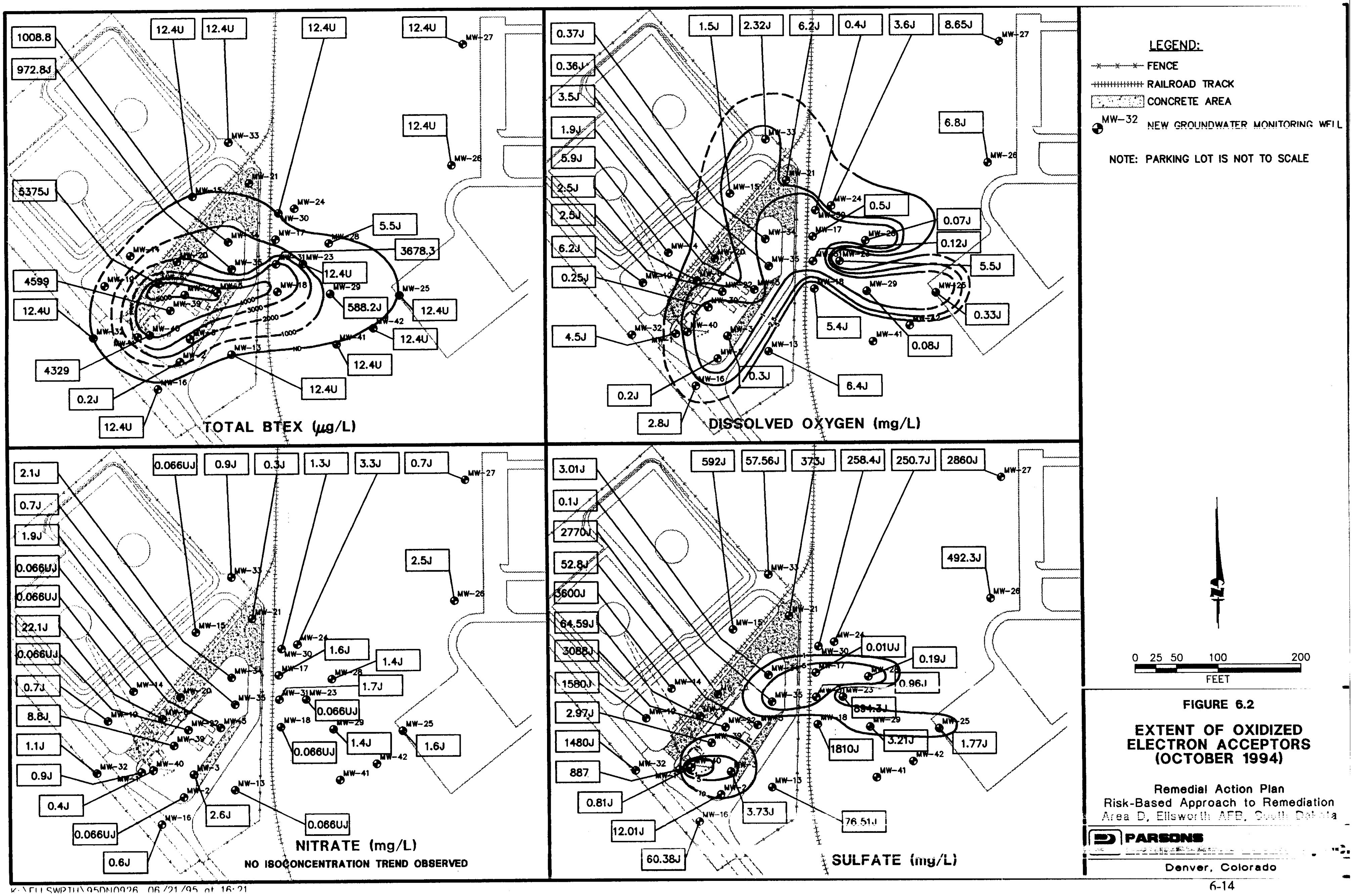

FIGURE 6.2

EXTENT OF OXIDIZED ELECTRON ACCEPTORS (OCTOBER 1994)

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naphthalene and BTEX compounds by nitrate reduction also will yield significant amounts of free energy for microbial use, nitrate reduction is not as energetically favorable as other potential redox reactions. However, nitrate reduction may take precedence over denitrification at the Area D as the groundwater becomes more reducing. As conditions become more reducing, nitrate is used as an electron acceptor via nitrate reduction. However, nitrate can only function as an electron acceptor in microbially-facilitated fuel hydrocarbon degradation reactions if the groundwater system has been depleted of oxygen (i.e., the groundwater must be functionally anaerobic). Oxygen is toxic to the enzyme systems used for electron transfer and energy production of nitrate-reducing microorganisms (McCarty, 1972).

Concentrations of both nitrate and nitrite were measured at groundwater monitoring wells in October 1994. Figures 6.2 and 6.3 present the analytical data for the oxidized nitrate and reduced nitrite, respectively. Figure 6.2 shows that there is no apparent depletion of nitrate near or downgradient of the source area relative to measured background concentrations. However, it is important to note that nitrate was detected at concentrations approaching the analytical detection limit in background sampling locations. This means that there is little nitrate mass naturally available at Area D to be used to oxidize fuel hydrocarbons.

Figure 6.3 confirms that nitrate is not being reduced to nitrite to facilitate microbiologically-mediated reactions involving fuel hydrocarbons. Thus, although measured Eh (pe) levels at the site suggest that the oxidizing potential of the groundwater has been reduced sufficiently so that denitrification and nitrate reduction can occur (Figure 6.1), analytical data demonstrate that sufficient nitrate is not available to be used as a potential electron acceptor.

6.4.4 Dissolved Manganese Concentration

Manganese also can be used as an electron acceptor to facilitate the oxidation of naphthalene and BTEX compounds under anaerobic and slightly reducing conditions. In fact, as Figure 6.1 shows, manganese reduction can be microbially facilitated in groundwater conditions similar to those required to support denitrification. The reduction of manganese to oxidize naphthalene and BTEX compounds yields essentially as much free energy to the system as aerobic respiration. Under anaerobic and slightly reducing conditions, manganese reduction is the second most energetically favorable redox reaction that can be used to biodegrade naphthalene and BTEX compounds. Although a few groundwater samples were collected and analyzed for reduced forms of manganese, insufficient data were available to determine whether manganese is being utilized as an electron acceptor at the site. Manganese reduction has been conservatively excluded as a potential biodegradation process at Area D.

6.4.5 Ferrous Iron Concentrations

Although relatively little is known about the anaerobic metabolic pathways involving the reduction of ferric iron (Fe^{3+}), this process has been shown to be a major metabolic pathway for some microorganisms (Lovley and Phillips, 1988; Chapelle, 1993). Elevated concentrations of ferrous iron (Fe^{2+}) are often found in anaerobic

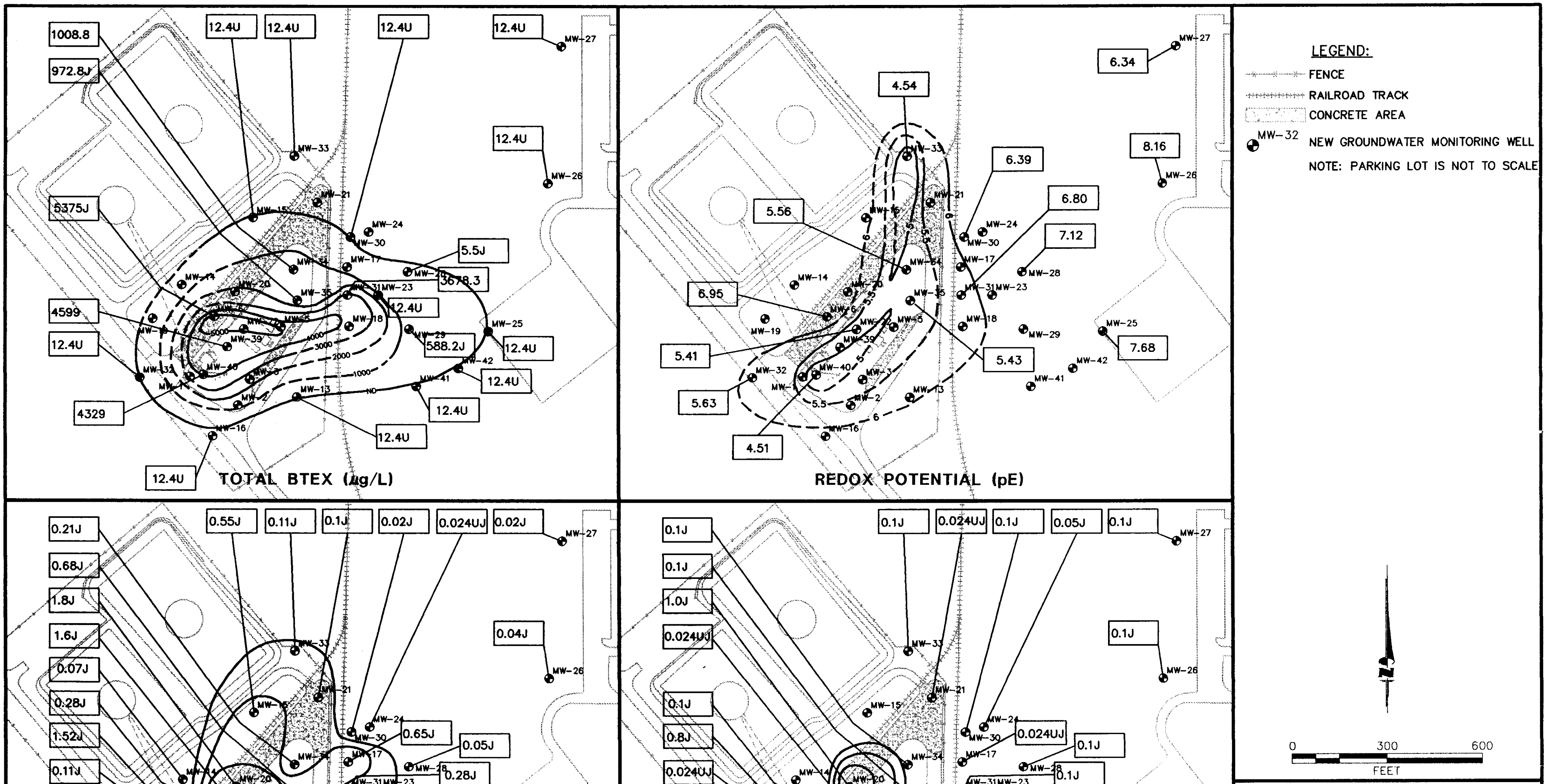

FIGURE 6.3

EXTENT OF BYPRODUCTS OF ELECTRON ACCEPTOR REDUCTION (OCTOBER 1994)

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groundwater systems. Concentrations of dissolved ferrous iron once were attributed to the spontaneous and reversible reduction of ferric oxyhydroxides, which are thermodynamically unstable in the presence of organic compounds such as BTEX and the PAH compounds. However, recent evidence suggests that the reduction of ferric iron cannot proceed at all without microbial mediation (Lovley and Phillips, 1988; Lovley *et al.,* 1991; Chapelle, 1993). None of the common organic compounds found in low-temperature, neutral, reducing groundwater could reduce ferric oxyhydroxides to ferrous iron under sterile laboratory conditions (Lovley *et al.,* 1991). This means that the reduction of ferric iron requires mediation by microorganisms with the appropriate enzymatic capabilities. The reduction of ferric iron results in the formation of ferrous iron.

To determine if ferric iron is being used as an electron acceptor at Area D, ferrous iron concentrations were measured at groundwater monitoring wells in October 1994. Figure 6.3 presents the analytical results for ferrous iron in groundwater at the site. Areas characterized by elevated concentrations of fuel hydrocarbons correspond well with areas of elevated concentrations of ferrous iron relative to measured background concentrations. Ferrous iron was measured near or below the detection limit in background wells and most wells located outside the area affected by fuel contamination. Concentrations of ferrous iron concentrations measured in groundwater monitoring wells within and immediately downgradient of the suspected source area ranged from 0.5 mg/L to 3.45 mg/L.

The correlation between elevated total dissolved hydrocarbon concentrations and elevated ferrous iron concentrations suggests that the iron-reducing microorganisms are using ferric iron to oxidize the contaminants. Because the reduction of ferric iron cannot proceed without microbial intervention, the elevated concentrations of ferrous iron that were measured in contaminated groundwater at Area D are strong indicators of microbial activity. These geochemical data suggest that iron-reducing microorganisms are present in the groundwater at the site, and that these microorganisms are using ferric iron to energize naphthalene and BTEX metabolism.

6.4.6 Sulfate and Sulfide Concentrations

Sulfate may be used as an electron acceptor during microbial degradation of fuel hydrocarbons under anaerobic and highly reduced conditions (Grbic-Galic, 1990). This redox reaction is commonly called sulfate reduction. Sulfate is reduced to sulfide during the oxidation of naphthalene and BTEX compounds. The Pierre Shale present at Area D is comprised of pyrite, which weathers to release sulfate. Weathering of the competent shale may be responsible for the elevated but generally nonuniform concentrations of sulfate measured in wells upgradient from or outside the area of dissolved contamination at Area D. Figure 6.2 shows the analytical results for sulfate in groundwater. It appears that sulfate concentrations are drastically reduced in regions of the source area and immediately downgradient of the source area. Interestingly, depleted sulfate regions seem to appear as two separate plumes. These data imply that there may have been at least two distinct release areas or release events at Area D. The depletion of sulfate within the contaminated area suggests that this compound is acting as an electron acceptor.

Hydrogen sulfide is produced when sulfate is reduced to oxidize naphthalene and BTEX compounds. Figure 6.3 shows the analytical results for hydrogen sulfide in groundwater. Elevated concentrations of hydrogen sulfide were detected in groundwater samples collected form the suspected source area. The production of hydrogen sulfide in areas with elevated fuel hydrocarbon concentration are strong indicators that sulfate is being utilized as an electron acceptor at Area D. The actual reservoir of sulfate available to indigenous microorganisms may be inexhaustible because of the mineral nature of the Pierre Shale.

6.4.7 Methane and Carbon Dioxide Concentrations

On the basis of free energy yield and oxidizing potential, the carbon dioxide-methane (CO_2-CH_4) redox couple also could be used to oxidize fuel hydrocarbon compounds to carbon dioxide and water once the groundwater is sufficiently reducing. To attain these reducing levels, other highly oxidizing chemical species such as oxygen, nitrate, and manganese must be reduced. This redox reaction is called methanogenesis or methane fermentation. Methanogenesis yields the least free energy to the system in comparison to other chemical species (Figure 6.1 and Appendix E). The presence of methane in groundwater at elevated concentrations relative to background concentrations is a good indicator of methane fermentation.

Carbon dioxide and methane concentrations were measured at groundwater monitoring wells in October 1994. Carbon dioxide and methane data are included in Appendix A. Analytical data on carbon dioxide were not used to estimate a potential reservoir of available electron acceptors at Area D. Methane was detected at only one groundwater sampling location near the source area at a concentration approaching the analytical detection limit (MW-39). The presence of methane in this groundwater sample may indicate methanogenesis is occurring in the center of the plume where redox conditions can be expected to be the most reducing. The mass of reactive organic material present in the saturated soil and groundwater is potentially sufficient to reduce the oxidizing capacity to levels required for methanogenesis. However, the limited amount of methane data and the measured Eh range of site groundwater preclude solid inferences that methanogenesis is occurring at the site.

6.5 THEORETICAL ASSIMILATIVE CAPACITY ESTIMATES

The preceding discussions have been devoted to determining if naphthalene and BTEX compounds are biodegrading at Area D. Analytical data on reduced and oxidized chemical species indicate that indigenous microorganisms are facilitating the oxidation of naphthalene and BTEX compounds by reducing certain electron acceptors to generate free energy for cell maintenance and production. The question of how much contaminant mass can be biodegraded must be addressed to assess the full potential for long-term intrinsic remediation of the site.

Mass-balance relationships can be used to determine how much contaminant mass can be degraded by each of the redox reactions that the microorganisms might use to make free energy available for cell maintenance and production. The stoichiometric relationship between the contaminant and the electron acceptor can be used to estimate the assimilative capacity of the groundwater. Now that the redox reactions that are operating at Area D have been defined, it is possible to estimate how much contaminant mass can be assimilated or oxidized by available electron acceptors. This analysis, when coupled with the biodegradation rate information discussed earlier (Table 6.1), will provide the basis for determining the potential for continued intrinsic remediation of groundwater contamination at the site.

Appendix E presents the coupled redox reactions that represent the biodegradation of naphthalene and each of the BTEX compounds. These tables also present the stoichiometric mass ratio of electron acceptors needed to oxidize naphthalene and each of the BTEX compounds. These stoichiometric mass ratios can be used to estimate the assimilative capacity of the groundwater at Area D. This is accomplished by first determining the initial mass of each electron acceptor available in the groundwater. Data on these chemical species were collected at sample locations upgradient of the site (i.e., sampling locations MW-19 and MW-32). As groundwater migrates from background areas into the source area, electron acceptors are brought into contact with hydrocarbon-degrading microorganisms and site contamination. This influent mass is divided by the mass of electron acceptors required to mineralize each of the fuel hydrocarbon compounds to estimate the intrinsic capacity of the groundwater to biodegrade each of the fuel hydrocarbon compounds.

Conservative estimates of the background concentrations of all of the electron acceptors that may be involved in the biodegradation of naphthalene and BTEX compounds are listed in Table 6.2. These concentrations are used to calculate the available or expressed assimilative capacity of each electron acceptor for naphthalene and BTEX based on the mass stoichiometric relationships presented in detail in Appendix E. Table 6.2 also presents the highest concentration of ferrous iron and hydrogen sulfide measured at the site. These concentrations are used to "back-calculate" the expressed assimilative capacity that is attributable to ferric iron and sulfate reduction, respectively. On the basis of these calculations, the groundwater at Area D has the intrinsic capacity to oxidize a concentration of approximately 2,700 μg/L of total BTEX per pore volume exchange of groundwater.

The maximum measured concentration of total BTEX in both 1991/1992 and 1994 exceeded the theoretical assimilative capacity of the groundwater at Area D. This estimate represents an upper-bound value of the assimilative capacity of the saturated soil and groundwater for BTEX compounds per pore volume exchange. Between January 1992 and October 1994, more than 240 pore volume flushes were completed. This means that contaminant mass in the source area may have been brought into contact with more than sufficient electron mass to facilitate degradation reactions. However, only a fraction of the actual electron acceptor mass brought in by groundwater will be used by microorganisms to facilitate BTEX and possibly naphthalene biodegradation. The total reservoir of electron acceptors will not be available to the microorganisms because of mass transfer, kinetic, and other biological and chemical limitations.

Some of the electron acceptor mass that is not used to oxidize BTEX may be used to facilitate the oxidation of naphthalene in saturated media. Site data suggest that the total BTEX compounds are more easily biodegraded than naphthalene. Even though the oxidation of naphthalene would yield more energy to the system (Appendix E),

TABLE 6.2
ESTIMATE OF ASSIMILATIVE CAPACITY OF SATURATED SOIL AND GROUNDWATER
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Electron Acceptor	Background Concentration (μg/L)	BTEX Assimilative Capacity[a/] (μg/L)	Naphthalene Assimilative Capacity[a/] (μg/L)
Oxygen	6,050	1,908.5	2,016.7
Sulfate	1,000	613.5	628.9
Ferric Iron [b/]	3,450	164.3	165.1
	Total	2686.3	2,810.7
	Maximum 1994 Conc.	5,375	300

[a/] Calculated based on the ratio of the total mass of electron acceptor required to oxidize a given mass of contaminants (Appendix E).

[b/] This represents the reduced form of the electron acceptor.

Assimilative capacity is expressed only as an estmate.

these compounds are more difficult to oxidize because of their more complex chemical structure. The assimilative capacity of saturated media at Area D for naphthalene can be estimated by using mass stoichiometric relationship. Table 6.2 also summarizes these estimates.

These estimates show that there is apparently a sufficient supply of electron acceptors in the saturated media at the site to both continue to sustain the rate at which naphthalene is being biodegraded. Based on these upper-bound estimates, more than 2,800 µg/L of naphthalene could be oxidized by electron mass not used to degrade the BTEX compounds.

In summary, naphthalene and BTEX compounds do not and should not exert a significant demand on the total assimilative capacity available at Area D. There is sufficient electron acceptor mass available at Area D to completely degrade the maximum measured concentrations of naphthalene and BTEX compounds. However, site data demonstrate that only a portion of the total assimilative capacity is apparently involved in biodegradation reactions, possibly due to kinetic, equilibrium, and mass transfer limitations. As long as the total assimilative capacity is not being used to facilitate contaminant biodegradation, slow biodegradation rates should be expected to persist at Area D. The effect of these processes on the nature and extent of contaminant migration that can be expected to occur at the site over time are quantitatively modeled in the next section.

6.6 PREDICTING CHEMICAL FATE OVER TIME

Understanding the effects of natural physical, chemical, and biological processes on chemicals is an important step in determining potential long-term risks associated with chemical migration in the environment. The behavior of BTEX compounds and possibly naphthalene under the influence of these processes must be quantified to estimate the likelihood and nature of a future release, to predict the extent that any chemical could migrate, and to assess the effects on chemical persistence, mass, concentration, and toxicity over time at the site. If destructive and nondestructive attenuation processes can minimize or eliminate the concentration of contaminants to which a receptor could be exposed, remedial action may not be warranted because no reasonable exposure pathway exists or the exposure pathway would result in insignificant risks. The focus of this final section is to predict how BTEX compounds and naphthalene will be transported and transformed over time in soils and groundwater based on site data and site-specific chemical release and transport models.

6.6.1 Source Contribution of Contaminated Soils

6.6.1.1 Leaching from Unsaturated Soils

The Seasonal Soil Compartment Model (SESOIL) was used to estimate the potential impacts to groundwater quality due to contaminants leaching from unsaturated soils. SESOIL is a one-dimensional vertical transport model for the unsaturated soil zone. The model was originally developed for the EPA (Arthur D. Little, Inc., 1981), and modified by the Oak Ridge National Laboratory and the Wisconsin Department of

Natural Resources (Hetrick and Scott, 1993). SESOIL is based on mass balance and equilibrium partitioning of the chemical between different phases (i.e., dissolved, sorbed, vapor, and pure). This model can be used to simulate the transport of chemical contamination to the atmosphere and groundwater. SESOIL is essentially a screening level model, because it uses less soil, chemical, and meterological data than other similar models. SESOIL is coupled with the Summers model (Summers *et al.,* 1980) to compute contaminant concentrations in the saturated zone below the unsaturated column. The model was applied as part of this evaluation to simulate chemical releases from unsaturated soil to groundwater. The objective of this quantitative assessment was to determine if unsaturated, contaminated soils are also likely to be a significant source of contaminants, particularly benzene, to groundwater at Area D.

The model requires several types of chemical- and site-specific data to estimate the concentration of a chemical in the soil, its rate of leaching toward groundwater, and the impact of other environmental pathways. SESOIL was operated in a monthly option mode to provide a better estimate of chemical movement through the unsaturated soil at Area D. Monthly meterological data for Ellsworth AFB was obtained from Flight Operations at the Base (Appendix E). The unsaturated soil column was conceptualized as 3 feet thick. This is an extremely conservative assumption since the depth to groundwater at the site is more than 10 feet bgs. However, this depth was selected to allow infiltrating precipitation to come into direct contact with the most contaminated soils, which are generally underlying the clayey near surface soils. The maximum concentration of BTEX in soils was used in the SESOIL simulations. Appendix E presents the SESOIL model input data.

The climate at the Base is classified as semi-arid continental with warm and dry summers and cold winters. Low rainfall in the area is believed to be the result of a "rain-shadow effect" created by the Black Hills to the west (EA, 1994). The net annual precipitation based on information from the National Oceanographic and Atmospheric Administration (NOAA) is calculated to be -24 inches. A negative value is obtained because the annual evapotranspiration is greater than the annual total precipitation. The SESOIL model results confirmed a negative net annual precipitation. Although infiltration does occur, the low rainfall and high evapotranspiration effectively minimized vertical transport of contaminants in the vadose zone under normal conditions at the site. However, the model also indicated that a large but short duration storm event could cause sufficient contaminant mass to leach from source area soils and increase the total BTEX concentration in underlying groundwater by about 25 µg/L.

Thus, the SESOIL model predicts that unsaturated soils could represent a long-term source of contamination to groundwater. Based on site-specific data and conservative model assumptions, contaminants could slowly partition from soils and dissolve into groundwater under normal conditions. A more rapid "pulse release" of contaminants into groundwater during storm events, which are common in the winter and spring, also is anticipated. These model results areconsistent with soil data collected to date at the site. Analytical soil results suggest that contaminants are generally occluded in site soils, but that contaminant mass could be slowly partitioning into groundwater over time. These soils also are expected to contribute a pulse of contaminant mass to groundwater during unusually high precipitation events.

6.6.1.2 Partitioning from Saturated Soils

Leaching of contaminants from saturated soils can also impact the type and magnitude of remedial action required at a site. Defining how BTEX compounds, and specifically benzene, partition from saturated soil and dissolve into groundwater based on site conditions can provide valuable information on predicting the nature of future groundwater quality impacts that may have to be remediated in the absence of reliable onsite exposure controls to protect onsite workers.

Chemicals sorbed to saturated soils can gradually partition or leach from and dissolve into groundwater. An equilibrium partition relationship was used to model how the BTEX compounds in saturated soils are expected to leach from and dissolve into groundwater at Area D. The most common equilibrium model used to describe the amount of contaminant that will remain sorbed to the soil and the amount of contaminant that will dissolve into groundwater is the distribution partition coefficient (K_D). The linear distribution partition coefficient is calculated by multiplying the chemical's solubility in water normalized for total organic carbon content (K_{OC}) and the fractional organic carbon content (f_{OC}) of the soil matrix. Appendix E presents the calculated K_D values for each of the BTEX compounds.

Leaching from saturated soils into groundwater was simulated for the site using a simple batch flushing model. Basically, a volume of contaminated soil was continually flushed with influent groundwater. New, uncontaminated groundwater would flow into the contaminated volume of source soils at the linear velocity of the shallow aquifer. Contaminants sorbed to the soil matrix would leach from the soil into the uncontaminated groundwater, which would then flow from the downgradient edge of the contaminated source soils. The amount of contaminant that would leach from the source soils into each new volume of uncontaminated groundwater depends upon the concentration of contaminant in the soil and the chemical-specific K_D. The leaching model calculations and input values are more fully described in Appendix E.

Model calibration and validation were completed for the predictive leaching calculations. Calibration was accomplished by matching maximum 1994 soil concentrations (sorbed mass) to the groundwater concentrations observed at the same location (dissolved mass). The simple batch flushing model was used to estimate the long-term effects of leaching on contaminant concentrations in soil and groundwater at the site. It is important to note that this calculation only accounts for the physical and chemical processes involved in COC leaching from saturated soils. This calculation does not consider how much COC mass could be biodegraded in saturated soils over time.

The leaching calculations presented in Appendix E indicate that saturated soils are not likely to be a long-term source of contaminant mass to groundwater. This is because contaminant mass is not effectively occluded in these soils to be leached slowly to groundwater. The low fractional organic carbon content and the observed maximum groundwater velocity at the site results in rapid partitioning from saturated soils to groundwater. This behavior was confirmed by the 1994 sampling results, where only very low levels of BTEX were measured in saturated soils at the site. However, these model results do indicate that once saturated soils become contaminated, either by downward infiltration of contamination through vadose zone soils or by seasonal fluctuations in the groundwater table elevation, contaminant mass will rapidly dissolved into and impact underlying groundwater quality.

6.6.2 Source Contribution of Weathering LNAPL

The presence of an isolated pocket of LNAPL floating on the groundwater table at Area D has been identified as a potentially significant source of contaminant mass to groundwater. OILENS, which is one of the major modules of the EPA's Hydrocarbon Spill Screening Model (HSSM), was used to quantify the dissolution of contaminant mass from LNAPL. The HHSM code was developed by the EPA's Robert S. Kerr Environmental Research Laboratory to aid in estimating the impacts of LNAPL releases on groundwater (EPA, 1994b). The areal extent of the suspected pocket of LNAPL was used to estimate the mass transfer of chemical constitutents in the LNAPL to the groundwater via infiltrating rainfall and dissolution caused by flowing groundwater. OILENS calculates the mass load to groundwater from infiltrating rainfall based on volume flux (Darcy velocity) of the precipitation influx and the equilibrium concentration for the chemical in contact with water. OILENS calculates the mass load to groundwater from dissolution based on equilibrium between the base of the LNAPL lens and the migrating groundwater. Relevant explanations of the mathematical basis for OILENS are included in Appendix E (from EPA, 1994b).

LNAPL was conservatively assumed to impact an area of approximately 18,225 ft^2 in the vicinity of MW-6. Estimates of the mass fraction of BTEX in the LNAPL were based on analytical data collected at the site (Section 4). The maximum groundwater velocity of 0.4 ft/day was used (Section 3) to develop the most conservative estimate of mass loading. Appendix E presents the model input parameters and calculations related to OILENS.

The model predicted that a maximum of 90 milligrams of total BTEX initially could dissolve into underlying groundwater per day as a result of direct dissolution from LNAPL. An additional maximum of 31 milligrams of total BTEX could be added to the groundwater per day if sufficient precipitation infiltrates into and percolates through unsaturated, contaminated soil and the LNAPL lens at the site. These source term estimates are based on the chemical mass measured in the soil and LNAPL collected at MW-6 during the 1994 sampling event. However, less contaminant mass will be available to act as a continuing source to groundwater as the soil and LNAPL weathers over time. To account for these source weathering effects, OILENS was used to simulate mass loading rates over time. The initial mass of contaminants in the source was sequentially reduced by the mass that had already partitioned from and dissolved into groundwater. As the source of contamination weathered, lower mass loading rates would be expected. Table 6.3 presents the mass loading rates expected over time at Area D when the effects of weathering are considered. Appendix E shows an example calculation on how weathering impacts were factored into OILENS. Sufficient contaminant mass was measured in the LNAPL at Area D to act as a continuing source of groundwater contamination for 11 years. After that time, the contaminant mass in the residual LNAPL pocket would be depleted, although residual contamination occluded in source area soils could still continue to act as a low-level source of groundwater contamination..

TABLE 6.3
LNAPL DISSOLUTION RATES DURING NATURAL WEATHERING ONLY AND WITH SOURCE TERM REDUCTION
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Year	Dissolution Rate Natural Weathering Only (g/day)	Dissolution Rate Natural Wearthering and Source Term Reduction (g/day) [a/]
0	0.090	0.090
1	0.060	0.045
2	0.050	0.024
3	0.040	0.023
4	0.040	0.022
5	0.030	0.021
6	0.020	0.020
7	0.020	0.019
8	0.020	0.018
9	0.010	0.017
10	0.010	0.016
15	0.000	0.012
20	0.000	0.000

[a/] Source term reduction assumes 25% reduction in area impacted by contamination during the first two years.

6.6.3 Contaminant Transport and Fate in Groundwater

A numerical modeling approach was selected to investigate the transport and fate of dissolved BTEX compounds in groundwater at Area D. The mathematical model Bioplume II was used to simulate the behavior of total BTEX in groundwater at the site over time. The two primary objectives of this modeling effort were to determine the maximum extent of contaminant migration toward the nearest downgradient Base property boundary and to characterize the anticipated concentration of total BTEX in groundwater as a function of distance and time at the site. The mathematical model developed for this effort accounts for the natural physical, chemical, and biological processes documented to be occurring at Area D. This type of model is useful in defining and understanding the various factors that may contribute most to potential future exposure to site-related contamination (EPA, 1992a).

6.6.3.1 Model Overview

The Bioplume II model code incorporates advection, dispersion, adsorption, and biodegradation to simulate BTEX plume migration and degradation. The computer code used to simulate these processes is based upon the US Geological Survey Method of Characteristics (USGS MOC) two-dimensional (2-D) solute transport model of Konikow and Bredehoeft (1978). The USGS MOC model accounts for advective, dispersive, and adsorptive mechanisms only. The model was modified by researchers at Rice University for the EPA to include a biodegradation component based on the work of Borden and Bedient (1986). The model was configured to simulate total BTEX loss from biodegradation using the conservative site-specific biodegradation rates derived in Section 6.3.4. The site-specific biodegradation rate constant for total BTEX presented in Table 6.1 (i.e., 0.00115 day^{-1}) was used to simulate the effects of biological processes on contaminant fate over time. Total electron mass was not used to calculate total BTEX mass removal by destructive attenuation processes over time. This is an important element of this model, because it ensures that biodegradation effects as calculated from actual field-scale evidence are incorporated into the quantitative chemical fate assessment. A complete description of the Bioplume II model developed for this site is included in Appendix E.

The Bioplume II model developed for Area D used site-specific data and conservative assumptions about governing physical, chemical, and biological processes. The use of a two-dimensional model is appropriate at Area D because the saturated interval is thin, and the local flow system, as defined by groundwater elevation data and the deep, underlying Pierre Shale (estimated to be about 860 feet thick), will likely prevent significant downward vertical migration of dissolved BTEX contamination. Based on the data presented in Section 3, the shallow saturated zone was conceptualized and modeled as a shallow unconfined aquifer composed of gravels, sands, silts, and clays all overlying fractured bedrock. Saturated thickness varies significantly over the site as a result of a paleochannel running to the southeast from the source area at Area D. On the basis of aquifer thickness and dissolved BTEX data (Sections 3 and 4), the saturated thickness of the aquifer was estimated as a constant 3 feet in the model. Groundwater contamination was assumed to impact the entire saturated zone.

Based on the estimated potentiometric surface at the site, groundwater appears to flow from the source area to the northeast toward a large bowl-shaped depression beneath the fuel yard and adjacent to the site. Yet, field data suggest that groundwater flows more readily through the unconsolidated gravel layer resting on the shale. The presence of dissolved contamination southeast of the source area may be the result of contamination migrating along preferential contaminant transport pathways. The Bioplume II model was used to estimate the maximum travel distance by concentration from the source area expected at the site. The model was used to predict the maximum distance dissolved BTEX could travel along these preferential channels. This modeling approach and the subsequent modeling results are likely to overestimate the extent of migration and underestimate the beneficial effects of natural chemical attenuation processes that will actually be observed at the site. The basis for this modeling approach and expected impacts of modeling results is further described In Appendix E.

The Bioplume II model was also used to simulate the effects of implementing source reduction technologies such as bioventing and passive product recovery. The reduction in the nature and extent of contaminant sources at the site reduced the amount of contaminant mass that could partition into groundwater over time. The predicted reduction in the source term as a result of implementing some type of LNAPL reduction technology is presented in Table 6.3. This reduced source term was used to investigate the long-term effects of source reduction technologies such as bioventing and passive product recovery methods on the extent of dissolved contamination at the site. These specific model results will be presented and discussed in Section 8. The model results presented in this section account for the effects of non-engineered processes on contaminant transport and fate.

6.6.3.2 Model Calibration

Part of the modeling strategy for this site was to identify and develop a groundwater flow and contaminant model that can be used to reasonably simulate observed site conditions. The ideal situation would be to have a limitless supply of site data to use in the creation of a groundwater model that would then generate output that was absolutely representative of site conditions. However, the economics and logistics of collecting enough site data to satisfy each model input parameters would be enormous. Sites with incomplete site data are usually modeled by performing a model calibration rather than returning to the field for additional data to check model predictions. Model calibration is the process of systematically adjusting specific model input parameters within an expected range until the resulting model output is a reasonably good match to actual field data. Model calibration is an essential step toward developing an appropriate and defensible mathematical tool to predict contaminant behavior in a complex system (Freeze and Cherry, 1979; National Research Council, 1990).

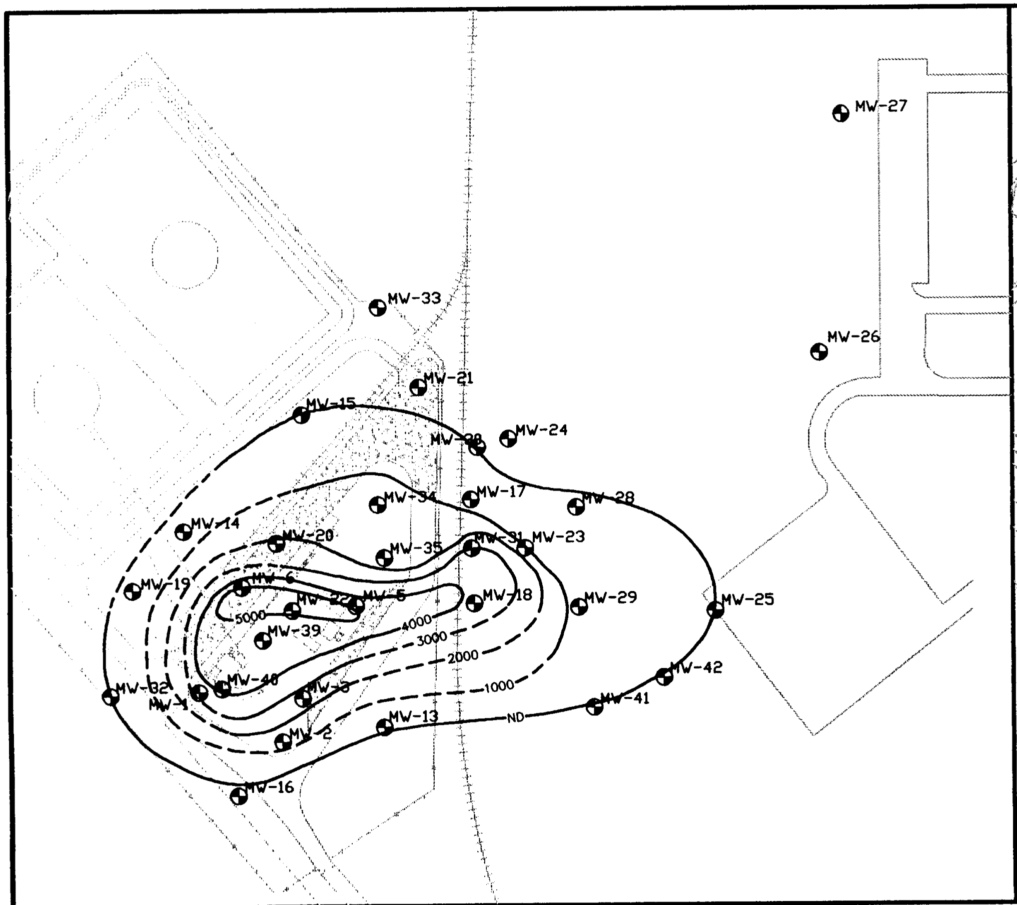
Site data collected during the 1991/1992 and 1994 sampling events were used to calibrate the Bioplume II model for Area D. The model for Area D was calibrated by directly adjusting and calculating a select range of model parameters until good agreement between model predictions and site conditions was achieved. Only trasmissivity was adjusted in a trial-and-error fashion as part of the calibration of the Bioplume II model for this site. The Bioplume II model developed for this site was calibrated using the highest transmissivity values that could be reasonably observed at the site based on available hydraulic conductivity data. This is a critical conservative assumption that will serve to overestimate the extent of contaminant migration and underestimate the degree of contaminant mass destruction over time at the site. The use of the site-specific degradation constant in the model means that contaminant mass removal will become less effective as a function of distance as contaminant velocities increase. Site-specific data on the total BTEX biodegradation coefficient, chemical retardation, dispersivity, and source term loading rates were used directly and not varied during model calibration.

The calibration of the Bioplume II model developed for Area D can be evaluated by comparing how closely model predictions match recorded site conditions in terms of groundwater hydraulics and contaminant plume shape and migration. The final calibrated model resulted in a reasonable representation of groundwater flow patterns. The root-mean-square error between actual and observed groundwater elevation heads was 0.50 feet, which translates to a model error of less than 8 percent given a total head drop of 6.36 feet over the model domain (see Appendix E for more details). This error value suggests that model errors are only a small part of the overall model response. Additionally, a good agreement between the simulated total BTEX plumes and the observed total BTEX plumes was achieved. Figure 6.4 compares the modeled total BTEX plume for late 1994 [which is 4 years after a primary release at the site in 1990 (Section 4)] to the total BTEX plume observed in August through November 1994. Although the simulated BTEX concentrations in the center of the plume were slightly less than observed at the site, the general geometry of the BTEX plume was a good representation of 1994 site conditions.

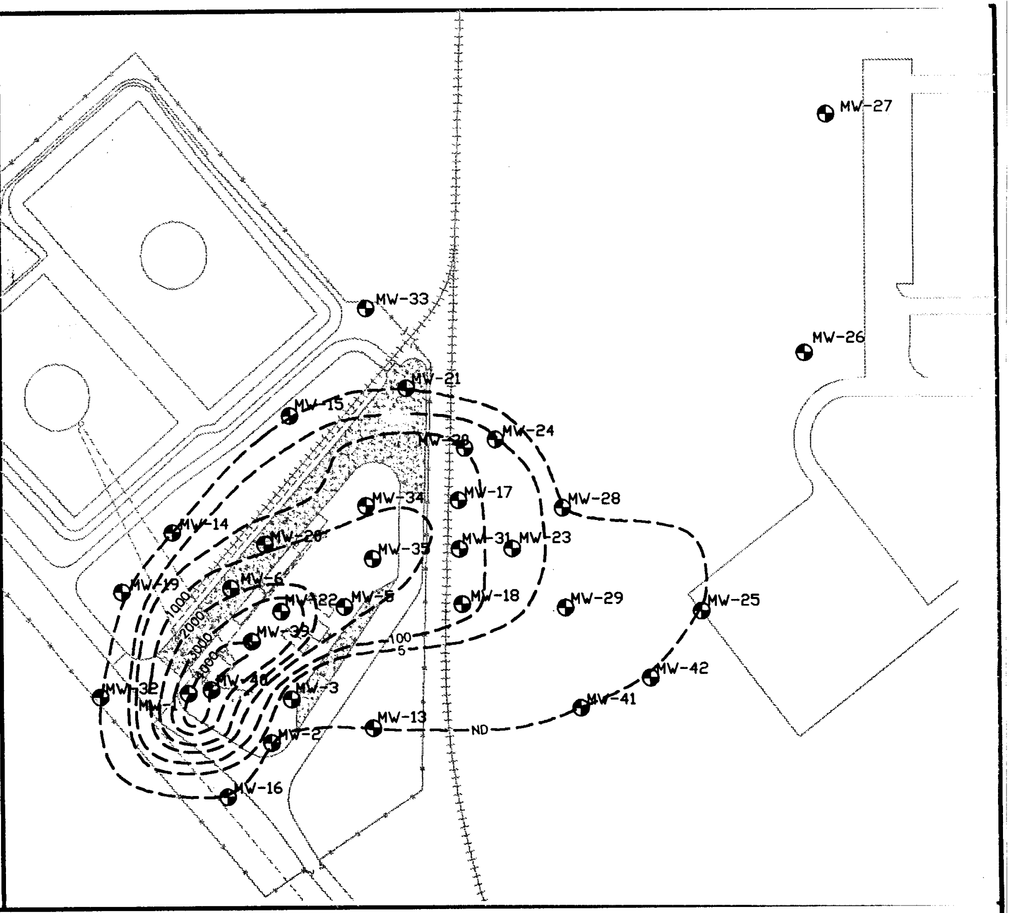
Further support that the model reasonably represents site conditions is obtained by comparing model predictions on how the plume probably conformed to 1991/1992 fuel spill survey data. The Bioplume II model predicts that the plume will migrate approximately 45 feet per year in the first few years following a fresh release of fuel. This means that the model predicts the dissolved BTEX plume will expand about 130 feet downgradient in about 3 years (January 1992 to late 1994). This type of behavior is consistent with field-scale evidence of plume dynamics over time. Low concentrations of dissolved BTEX contamination were detected in 1991/1992 approximately 180 feet upgradient from the leading edge of the dissolved BTEX plume defined in 1994. This means that the model likely overestimates how far contaminants can migrate in groundwater under the influence of both nondestructive and destructive chemical attenuation processes. The calibrated Bioplume II model was determined to be a reasonable and conservative estimate of actual field conditions, and sufficient to be used to develop predictive chemical fate estimates.

6.6.3.3 Sensitivity Analysis

The Bioplume II model calibration described in Section 6.6.3.2 is a non-unique solution for conditions at Area D. Nearly every groundwater model can have more than one plausible solution because of the number of variable model input parameters and the complex interactions between them (Anderson and Woessner, 1992). Because a model calibration does not quantify the uncertainty or reliability of the calibrated results, a model calibration should always be followed by a sensitivity analysis. A



DISSOLVED TOTAL BTEX
OBSERVED IN 1994



MODELED DISSOLVED TOTAL BTEX
IN 1994

LEGEND:

FENCE
RAILROAD TRACK
CONCRETE
MW-2 SAMPLING LOCATION
GROUNDWATER MONITORING WELL
LINE OF ESTIMATED EQUAL TOTAL BTEX IN $\mu g/L$ (DASHED WHERE INFERRED)

NOTE: PARKING LOT IS NOT TO SCALE

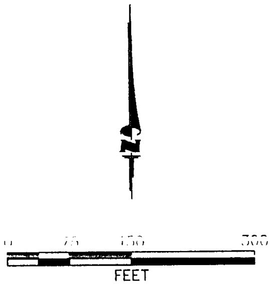


FIGURE 6.4

COMPARISON OF MODELED vs OBSERVED GROUNDWATER TOTAL BTEX PLUMES

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sensitivity analysis helps quantify the uncertainty in a model calibration by observing changes in modeled output produced by specific changes in model input parameters.

Based on the work of Rifai *et al.* (1988), the Bioplume II model is most sensitive to changes in the coefficient of reaeration (which was set equal to the site-specific degradation coefficient in this model to simulate biodegradation), the coefficient of anaerobic decay (which was not used in this model), and the hydraulic conductivity of the aquifer media. The Bioplume II model is typically less sensitive to changes in the retardation factor, porosity, and dispersivity. For the sensitivity analysis for the Area D model, only hydraulic conductivity (and therefore transmissivity), the coefficient of reaeration (i.e., site-specific biodegradation rate constant), and the retardation factor were varied. A detailed discussion of the sensitivity values used and the sensitivity results is presented in Appendix E.

The results of the sensitivity analysis suggest that the calibrated Bioplume II model is a good representation of site conditions. With respect to contaminant migration, the biodegradation rate constant (Table 6.1) is the parameter to which the model is most sensitive. Small variations in this parameter produce substantial changes in how far the total BTEX plume migrates and affects the maximum concentrations of total BTEX predicted to be present in the groundwater at the site at any time. Hydraulic conductivity is the model parameter with the next greatest influence on predicted results. The retardation coefficient follows hydraulic conductivity in terms of how much these input parameters can affect model results. The retardation coefficient had little effect on either contaminant concentrations or migration distance when specific input values were varied up to 25 percent from the calibrated input values.

6.6.3.4 Model Results

The attenuation of BTEX compounds and naphthalene by both nondestructive and destructive contaminant attenuation processes will affect the concentration of the contaminants in the affected media over time and distance at the site. In addition to the effects of nondestructive attenuation processes, site characterization data indicate that the BTEX compounds and possibly naphthalene are slowly biodegrading in saturated soils and groundwater at Area D. Destructive contaminant attenuation processes will continue to minimize total dissolved contaminant mass and limit contaminant concentrations and migration over time (Sections 6.3, 6.4, and 6.5). The assimilative capacity of the saturated soils and groundwater at Area D were shown to be sufficient promote aerobic and anaerobic biodegradation rates (Table 6.2). Although biodegradation of contaminants is relatively slow at this site, these processes can have a significant impact on chemical mass, concentration, mobility, persistence, and toxicity over time at Area D.

This is important since the screening exposure pathway analysis completed in Section 5 concluded that the only potential receptors for site-related contamination may be offsite receptors who could be exposed to groundwater contamination if contaminants were to migrate to distant, off-site locations at hazardous concentrations. No reasonable exposure pathway involving onsite receptors is complete at this site given the current and foreseeable uses of the Area D. Onsite workers could only come into contact with contaminated soils and groundwater as a result of deep excavation activities.

Thus, the Bioplume II model developed for Area D was employed to quantitatively investigate whether existing concentrations of BTEX compounds may eventually pose a threat to offsite receptors. Model predictions also provide quantitative estimates of when state promulgated groundwater quality standards can be achieved at every point in the shallow aquifer at the site. The calibrated Bioplume II model was first run for a period of 40 years to predict chemical behavior in groundwater in the absence of any engineered remediation activities. (See Section 8 for a discussion of the model predictions when LNAPL source reduction is implemented at the site.) The model was initiated at the time coinciding with the suspected release of JP-4 at the site first identified in September 1990. Therefore, no dissolved BTEX was present in groundwater at the start of the model simulation. The mass of total BTEX that could partition into the groundwater was calculated as part of the source release analysis discussed in the previous section.

Figure 6.5 shows the expected extent of total BTEX migration and relative distribution of BTEX concentration in the shallow aquifer at Area D in 5 years (i.e., by the year 1999), 10 years (i.e., the year 2004), 20 years (i.e., the year 2014), and 30 years (i.e., the year 2024). By the year 1999, the maximum concentration of total BTEX near the source area is expected to decrease to about 3,000 µg/L. The model predicts that the migration of the dissolved plume should slow within 10 years. The Bioplume II model predicts that the total BTEX plume will migrate to its maximum extent in 20 years, or by the year 2014. Model results suggest that detected concentrations of total BTEX (most likely benzene) will migrate an additional maximum of 375 feet downgradient from the 1994 leading edge of dissolved contamination. The concentration of total BTEX at the source area, upon reaching the full extent of expected plume migration (year 2014), is approximately 85 µg/L, which is less than 2 percent of the maximum dissolved total BTEX concentration measured at this region in October 1994. By the year 2024, the entire plume has been effectively attenuated, and the maximum residual concentration of total BTEX at the site will be approximately 5 µg/L.

On the basis of these simulations, it appears that natural hydrodynamic and chemical attenuation processes should be sufficient to minimize plume migration and eventually reduce contaminant concentrations in groundwater below state standards before any reasonable exposure pathway could be completed.

6.7 CONCLUSIONS

This section has focused on explaining how and why BTEX compounds and naphthalene in saturated soil and groundwater at Area D can be effectively attenuated by natural nondestructive and destructive processes. The important findings of this section are summarized as follows:

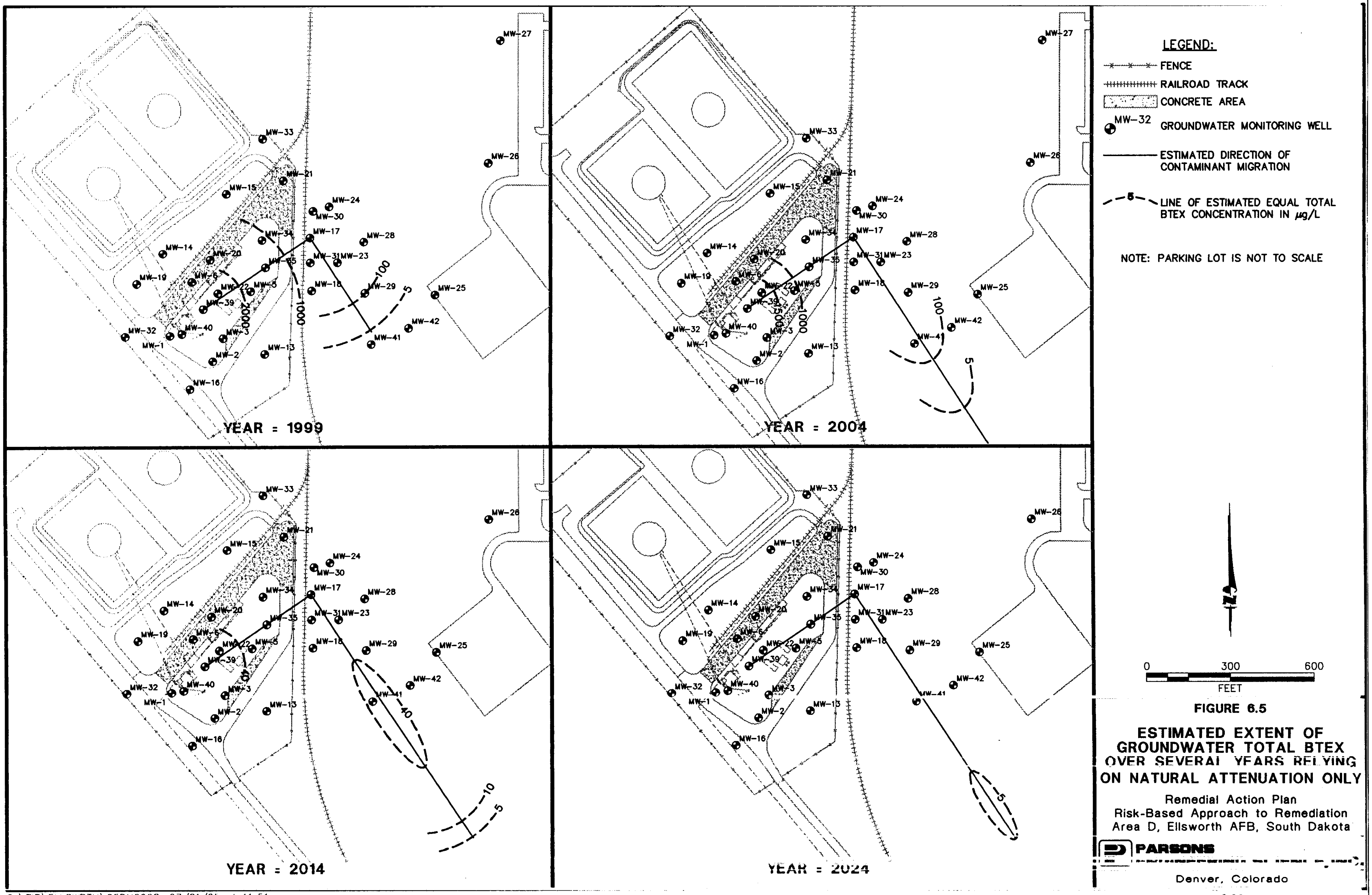

FIGURE 6.5

ESTIMATED EXTENT OF GROUNDWATER TOTAL BTEX OVER SEVERAL YEARS RELYING ON NATURAL ATTENUATION ONLY

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- BTEX compounds and possibly naphthalene are biodegrading in saturated soils and groundwater at Area D via oxygen reduction, ferric iron reduction, sulfate reduction, and possibly methanogenesis at rates slightly less than those found in the technical literature;
- The continuing introduction of contaminant mass into the groundwater from a small leak could be masking much higher biodegradation rates;
- Site-specific biodegradation rate estimates and site-specific theoretical assimilative capacity estimates confirm that measured concentrations of contaminants in saturated soil and groundwater can be completely but slowly biodegraded by natural processes;
- The HSSM model code predicts that the existing LNAPL suspected to be present at the site will act as a significant source of groundwater contaminants for about an additional 11 years;
- The SESOIL model code indicates that contaminants can slowly leach from soils and dissolved into groundwater over time under normal conditions, but unusually high precipitation events would be required to release a significant mass of contaminants into the groundwater;
- A simple batch flushing model indicates that contaminants will be mobile in saturated soils, because the constituents are not expected to be effectively occluded in saturated soils;
- The Bioplume II model code suggests that natural chemical attenuation processes will be sufficient to halt the forward migration of the dissolved plume within 20 years, and to uniformly reduce concentrations of BTEX compounds in groundwater to below state standards within 30 years; and
- The quantitative site-specific chemical fate assessment indicates that, although additional plume migration is anticipated, natural processes should be sufficient interrupt potentially significant exposure pathways to offsite receptors.

Based on this site-specific analysis, Area D could be considered for classification as an inactive status site in accordance with SDDENR guidance in about 20 years (when additional forward plume migration is halted) without implementing additional engineered remedial activities. This analysis demonstrates that contaminant concentrations at the site are not expected to increase over time and do not and will not present a significant health or environmental risk (SDDENR, 1994). However, it may be necessary to implement some level of source reduction at the site to minimize long-term effects of soil contamination and LNAPL on underlying groundwater quality and to strictly comply with the stated requirements of the inactive status classification. Section 7 documents the expected effectiveness of several low-cost source reduction technologies that could be used to remediate LNAPL and/or contaminated soils at the site.

SECTION 7

PILOT TESTING OF SOURCE REMOVAL TECHNOLOGIES

Section 6 of this RAP shows that both destructive and nondestructive attenuation processes should be effective at minimizing contaminant migration and reducing contaminant mass at Area D at Ellsworth AFB. This analysis was based on available site data for soil and groundwater. Selected source removal technologies also were evaluated at Area D as part of this field test in the event that engineered source removal is required to protect human health and the environment or to reduce the total time and cost of remediation. Although product removal technologies were not pilot tested by Parsons ES at Area D, free product recovery is briefly discussed in this section and included as a component of two remedial alternatives discussed in Section 8. To achieve SDDENR inactive status, potential fuel system leaks must be repaired, and recoverable LNAPL must be removed from the site to ensure that a continuing source of groundwater contamination does not exist.

A biosparging test, originally planned to be conducted at Area D (ES, 1994a), was not completed after it became apparent that the permeability and saturated thickness of the majority of the shallow aquifer were very minimal. A borehole drilled for the installation of a biosparging well did not appear to encounter a saturated zone above competent Pierre Shale.

A pilot-scale bioventing test was conducted at Area D by ES in 1993 and 1994 as part of a separate AFCEE remedial technology demonstration. Detailed results of initial bioventing pilot testing at Area D can be found in the *Interim Pilot Test Results Report for Area D Bulk Fuel Storage and Building 102 Base Fuel Station, Ellsworth AFB, South Dakota* (ES, 1993a). One-year soil sampling results and other test results are summarized in Section 7.2.

7.1 LEAK TESTING

Prior to the installation of a product recovery system at Area D, all transfer lines and USTs in the fuel system at Area D should be pressure tested to assure that any possible leaks have been identified and repaired. According to Ellsworth AFB personnel, all pipelines, ASTs, and USTs at Area D were pressure tested in 1993 and 1994. All tanks passed testing; however, laboratory analysis of a product sample collected from MW-6 in December 1994, indicated that the LNAPL present was chemically comparable to typical fresh JP-4 jet fuel (Table 4.1). This indicates that there may be a continuing leak in either a UST or a transfer line at the site. MW-6 is located immediately adjacent to two fuel transfer lines that supply fuel from the ASTs at the site to the pumping facilities in Building 8215. Ellsworth AFB personnel were made aware of the result of the mobile LNAPL screening and have scheduled the lines and tanks in the fuel yard for additional pressure testing. In 1995, a leak-detection system was installed at the site to detect leaks from the gasoline and diesel USTs near the center of the site. To date, no leak-detection system has been installed to detect subsurface releases from the fuel transfer lines at the site.

7.2 FREE PRODUCT RECOVERY

Prior to remediating dissolved contamination at Area D, all sources of continuing groundwater contamination must be remediated. The small area of free-phase product (mobile LNAPL) observed in MW-6 is a source of dissolved BTEX compounds in groundwater at Area D. Pilot testing of free product removal technologies has not been performed at the site. However, an LNAPL baildown and recharge test was performed by Parsons ES at MW-6 in October 1995. Results of the test are presented in Table 7.1. Product thickness recovery in the well during the test was very slow, indicating that active product recovery may not be an effective technique at the site. It is suggested that passive skimming or wicking technology be considered for mobile LNAPL recovery at Area D. This technology has been proven to be an effective, low-cost technology for sites with limited product thickness and slow recovery rates.

7.3 *IN SITU* BIOVENTING PILOT TESTING

7.3.1 Bioventing Well and Vapor Monitoring Point Installation

Bioventing wells VW-1 and VW-2 and vapor monitoring points MPA, MPB, and MPC were installed on August 23 through 27, 1993. Figure 7.1 shows the locations of VW-1, VW-2, MPA, MPB, and MPC. Figure 7.2 is a hydrogeologic cross-section showing the relationships of the screened intervals to subsurface soil intervals. Borehole logs and well construction diagrams for the bioventing system are included in Appendix B.

Two 4-inch-diameter polyvinyl chloride (PVC) air injection vent wells (VW-1 and VW-2) were installed in contaminated source area soils. Two wells were used to prevent preferential air flow into the gravel and cobble interval at the site. VW-2 was screened from 5 to 10 feet bgs through the silty clay interval. VW-1 was installed across the gravel interval with a screened interval from 10 to 17 feet bgs. Both wells were piped to one regenerative test blower, and valves were installed so that air flow into the subsurface through each screened interval could be regulated. Groundwater was not encountered in either of the wells during initial testing activities (ES, 1993a).

The three soil vapor monitoring points (MPA, MPB, and MPC) were screened in the unsaturated zone using 6-inch-long sections of 1-inch-diameter well screen centered at depths of approximately 5, 10, and 14 feet bgs. Thermocouples were installed at the 5- and 14-foot depths at MPA to measure soil temperatures. During initial testing activities in 1993, MW-24 was used as a background vapor monitoring point.

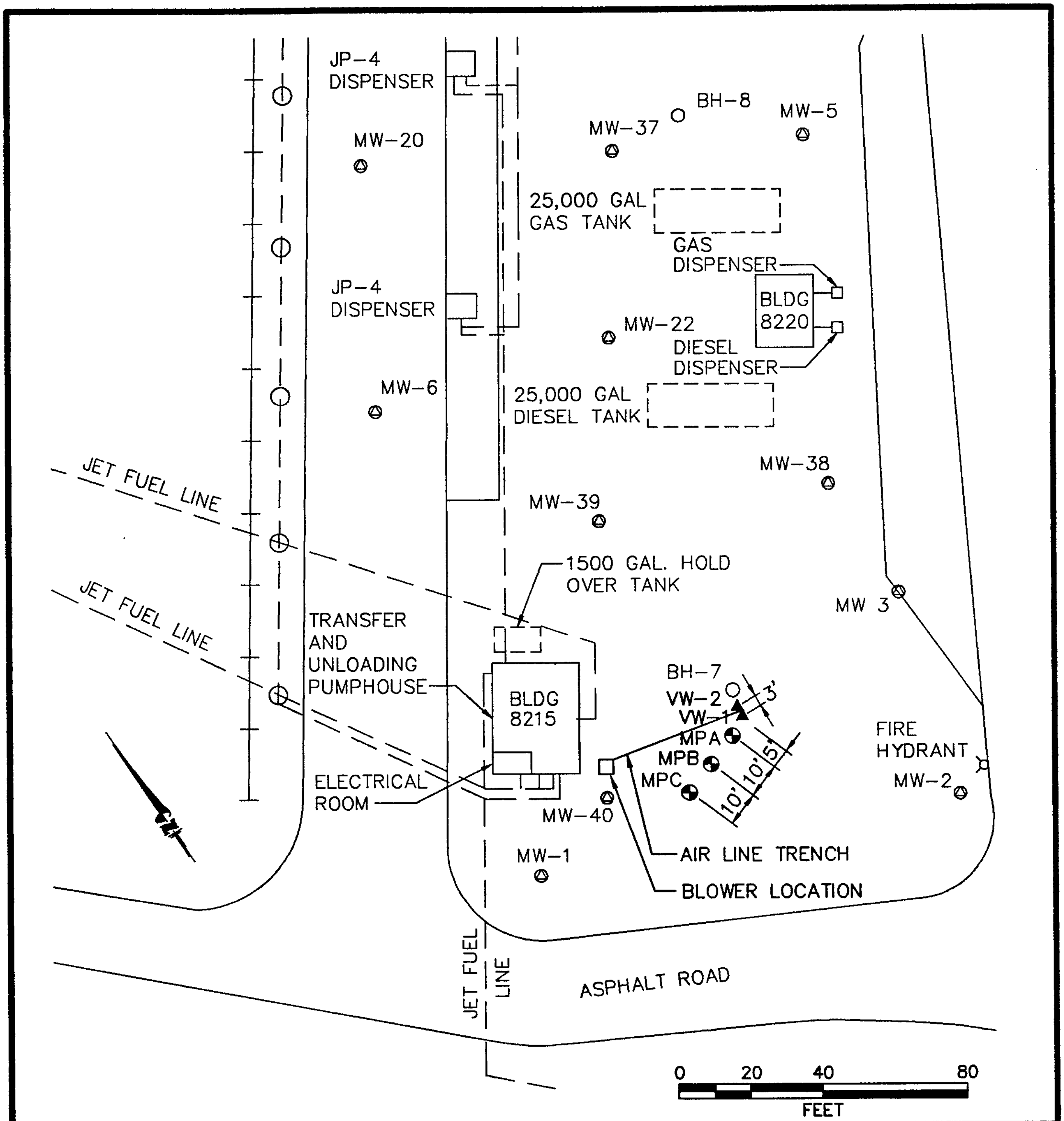
TABLE 7.1

RESULTS OF BAILDOWN TESTING PERFORMED AT MW-6
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Date	Time	Test Duration (hours)	LNAPL Thickness (inches)
10/12/95	0815 [a]	0	18.75
10/12/95	0845 [b]	0	0.25
10/12/95	1045	2	1.125
10/12/95	1330	4.75	1.375
10/12/95	1815	9.5	1.625
10/12/95	2215	13.5	1.625
10/13/95	0805	23.3	1.75
10/13/95	1400	28.25	1.75
10/13/95	1530	29.75	1.875

[a] Initial time at start of baildown test prior to removing product.

[b] Baseline time at start of baildown test after removing product.



LEGEND

MW-1 ⊗ EXISTING MONITORING WELL
BH-7 ○ SOIL BORING
▲ VENT WELL
● MONITORING POINT
+—+—+ RAILROAD SPUR

FIGURE 7.1

AS-BUILT VENT WELL AND MONITORING POINT LOCATIONS AREA D

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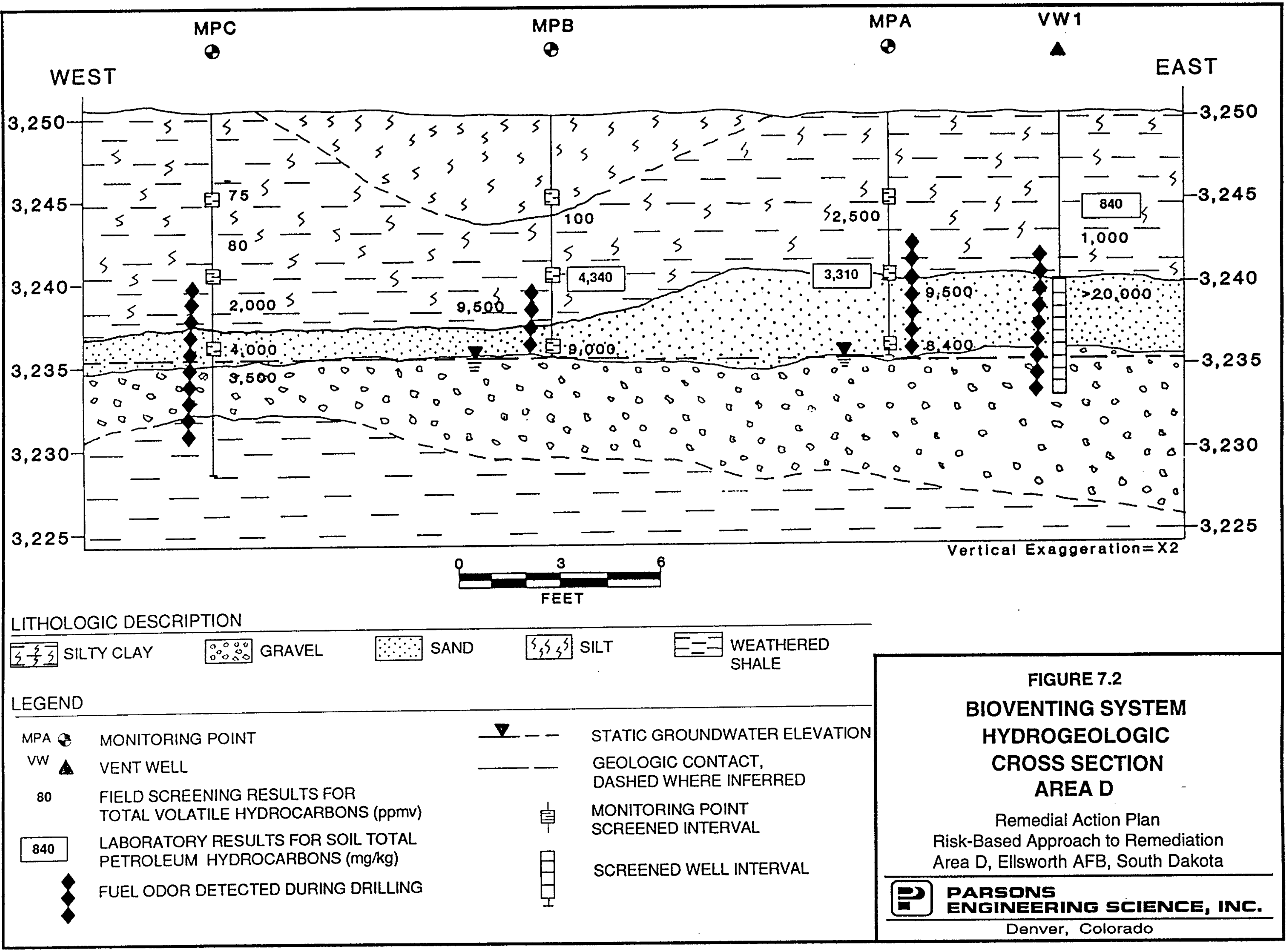

FIGURE 7.2

BIOVENTING SYSTEM HYDROGEOLOGIC CROSS SECTION AREA D

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7.3.2 Respiration Testing

In situ respiration testing was performed at Area D to determine oxygen utilization rates and potential biodegradation rates. Testing was performed by injecting a mixture of air (oxygen) and an inert tracer gas (approximately 1.5 percent helium) into three MP screened intervals (MPA-14, MPB-14, and MPC-10) and VW-1 for a 22-hour period. Oxygen loss and other changes in soil gas composition over time were then measured at these intervals and all other MP intervals that had elevated oxygen levels following the air injection period. Oxygen, TVH, carbon dioxide, and helium were measured for a period of approximately 24 hours following air injection. The measured oxygen losses then were used to calculate biological oxygen utilization rates. Oxygen levels at MPC-10 did not decrease, and this point was abandoned for use in the respiration test. Table 7.2 provides a summary of the oxygen utilization rates.

Because helium is a conservative, inert gas, the change in helium concentrations over time can be useful in determining the effectiveness of the bentonite seals between MP screened intervals. Because the observed helium loss was negligible, and because helium will diffuse approximately three times faster than oxygen due to oxygen's greater molecular weight, the measured oxygen loss was determined to be the result of bacterial respiration and was not due to faulty MP construction.

Oxygen loss occurred at high rates, ranging from 0.01669 percent per minute at VW-1 to 0.01986 percent per minute at MPA-10. At MPA-10, oxygen levels dropped from 19.0 percent to 9.0 percent in approximately 8.33 hours (Table 7.2).

Based on these oxygen utilization rates, an estimated 1,510 to 2,720 milligrams (mg) of fuel per kilogram (kg) of soil can be degraded each year at this site. This conservative estimate is based on an average air-filled porosity of approximately 0.068 liter per kg of soil, and a ratio of 3.5 mg of oxygen consumed for every 1 mg of fuel biodegraded. Biodegradation rates generally decreased over the first year of testing as easily degraded BTEX compounds were reduced in the soil (ES, 1993a).

7.3.3 Air Permeability Testing

An air permeability test was conducted according to AFCEE bioventing protocol document procedures (Hinchee *et al.*, 1992). Air was injected into VW-1 for 1.2 hours at a rate of approximately 15 standard cubic feet per minute (scfm) and an average pressure of 2.2 pounds per square inch (psi). The pressure measured at the MPs gradually increased at an irregular rate throughout the period of air injection. Due to the irregular pressure response, the steady-state method of determining air permeability was selected. A soil gas permeability value of 1.3 darcys, typical for a sandy silt, was calculated for this site. A radius of pressure influence of at least 25 feet was observed at the 10- and 14-foot depths.

The depth and radius of oxygen increase in the subsurface resulting from air injection during pilot testing is the primary design parameter for full-scale bioventing systems. Optimization of full-scale and multiple VW systems requires pilot testing to

TABLE 7.2

OXYGEN UTILIZATION RATES DURING INITIAL BIOVENTING PILOT TESTING
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Location	O_2 Loss[a] (%)	Test Duration[b] (min)	O_2 Utilization Rate[c] (%/min)
MPA-10	10.0	500	0.020
MPA-14	13.9	780	0.017
MPB-14	14.4	800	0.018
VW-1	8.7	520	0.017

[a] Actual measured oxygen loss.

[b] Elapsed time from beginning of test to time when minimum oxygen concentration was measured.

[c] Values based on linear best-fit oxygen decay curve.

determine the volume of soil that can be oxygenated at a given flow rate and VW screen configuration.

Table 7.3 presents the change in soil gas oxygen levels that occurred during a 18-hour injection period using the initial pilot test blower, and during a 41-hour period of injection using the extended pilot test blower unit. These periods of air injection produced changes in soil gas oxygen levels at the 10- and 14-foot MP screened intervals. Based on measured changes in oxygen levels, it is anticipated that the radius of influence for a long-term bioventing system will exceed 25 feet at all depths above competent Pierre Shale.

7.3.4 Pilot Test Results

After 1 year of operation, soil and soil gas samples were collected to determine the long-term effectiveness of the bioventing system during the risk-based site investigation in August 1994. Soil gas samples were collected on August 23, 1994, and soil samples were collected on August 28, 1994. Table 7.4 presents the tabulated analytical results from this sampling event and compares 1-year results to initial sampling results. Throughout the pilot test area, BTEX concentrations in soil and soil gas decreased appreciably. In several samples, BTEX levels decreased to below detection limits. Treatability testing indicates that *in situ* bioventing is a feasible and cost-effective method for remediating unsaturated hydrocarbon-contaminated soils within the source area at Area D.

TABLE 7.3

OXYGEN INFLUENCE IN SUBSURFACE DURING INITIAL BIOVENTING PILOT TESTING

REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

MP	Distance From VW (ft)	Depth (ft)	Initial O_2 (%)	Permeability Test O_2[a/] (%)	Long-Term System O_2[b/] (%)
A	5	5	17.0	16.0	NS[c/]
B	15	5	19.1	19.5	NS
C	25	5	17.0	21.0	NS
A	5	10	1.0	11.0	NS
B	15	10	19.2	19.2	NS
C	25	10	1.5	20.7	NS
A	5	14	0.5	20.4	NS
B	15	14	0.0	18.5	NS
C	25	14	0.5	4.5	7.5

[a/] Reading taken at the end of 18-hour air permeability test.

[b/] Reading taken after approximately 41 hours of injection using long-term test blower.

[c/] NS = not sampled.

TABLE 7.4
INITIAL AND 1-YEAR SOIL AND SOIL GAS ANALYTICAL RESULTS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte (Units)[a]	Sample Location-Depth (feet below ground surface)							
	VW-1		VW-2		MPC-10		MPA-14	
Soil Gas Hydrocarbons	Initial[b]	1-Year[c]	Initial	1-Year	Initial	1-Year	Initial	1-Year
TVH (ppmv)	58000	5.70	650	82	13,000	340	68,000	2,700
Benzene (ppmv)	230	0.02	2.90	< 0.005	26	< .014	290	< .014
Toluene (ppmv)	18	0.05	< 0.056	< 0.005	11	< .014	22	< .014
Ethylbenzene (ppmv)	19	0.02	1.30	0.21	8.3	0.99	23	6.7
Xylenes (ppmv)	49	0.08	4.80	0.85	15	3.8	53	29

	VW1-5		MPA-10		MPB-10	
Soil Hydrocarbons	Initial[d]	1-Year[e]	Initial	1-Year	Initial	1-Year
TRPH (mg/kg)	840	177	3,310	5,100	4,340	3,040
Benzene (mg/kg)	6.4	< 0.063	15	< 0.058	3.2	0.19
Toluene (mg/kg)	13	< 0.063	10	< 0.058	3.7	< 0.059
Ethylbenzene (mg/kg)	53	< 0.063	40	3.7	17	1.7
Xylenes (mg/kg)	310	0.57	190	21	57	9
Moisture (%)	23	20	13	13.3	17	15.2

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[a] TVH= total volatile hydrocarbons; ppmv=parts per million, volume per volume;
TRPH=total recoverable petroleum hydrocarbons; mg/kg=milligrams per kilogram.

[b] Initial soil gas samples collected on 8/26/93.

[c] 1-Year soil gas samples collected on 8/23/94.

[d] Initial soil samples collected on 8/24/93.

[e] 1-Year soil samples collected on 8/28/94.

SECTION 8

COMPARATIVE ANALYSIS OF REMEDIAL ALTERNATIVES

Sections 6 and 7 provided scientific documentation of natural attenuation processes and the potential benefits of mobile LNAPL removal and bioventing in accelerating the remediation of the source area at Area D. An initial screening of remedial approaches and technologies was completed, and several technologies were identified for possible use at Area D. A complete review of the initial screening process is included in Appendix H. Three remedial alternatives were developed using various combinations of natural attenuation, land and groundwater use controls, long-term monitoring, active source removal, and groundwater extraction and treatment. The objectives of Section 8 are to summarize the alternatives developed in Appendix H, to review the primary evaluation criteria used to compare these alternatives, and to complete a more detailed comparative analysis of each alternative in an effort to identify the most logical approach for remediating Area D. Each alternative is more fully explained in terms of its effectiveness, technical and administrative implementability, and cost. Following this evaluation, an implementation plan for the recommended alternative is summarized in Section 9.

8.1 SUMMARY OF CANDIDATE REMEDIAL ALTERNATIVES

Based on the initial remedial screening process, which is summarized in Appendix H, several remedial approaches and technologies were retained for the development of remedial alternatives. These technologies were selected to provide a range of passive to more active response actions, all of which will minimize contaminant migration, minimize increases in contaminant concentrations, and prevent receptor exposures (i.e., generally will meet SDDENR [1994] criteria for inactive status). The primary goal of all the proposed alternatives is to demonstrate that SDDENR inactive status is appropriate for Area D. This would allow the Air Force to close Area D without further active remediation even though groundwater contaminant concentrations exceed promulgated groundwater quality standards. As a secondary goal, each alternative also will eventually reduce groundwater contaminant concentrations to levels that meet groundwater quality standards at every point in the impacted area. Promulgated groundwater quality standards would be met in slightly different time frames and at different costs under each alternative. The following remedial approaches and technologies were retained for evaluation:

- Long-term groundwater monitoring;
- Limited land use controls;

- Groundwater use controls;
- Public education;
- Intrinsic remediation of soil and groundwater contamination;
- Groundwater extraction in source area via an interceptor trench;
- Extracted groundwater treatment with air stripping;
- Treated groundwater discharge via a sanitary sewer;
- Passive wicking for mobile LNAPL removal; and
- Air injection bioventing for treatment of residual LNAPL in source area.

The primary objective of source reduction technologies would be to more rapidly remove BTEX, especially benzene, and naphthalene contamination from the shallow groundwater and unsaturated soils near Building 8215, the suspected source area at Area D. Accelerating the removal of source contamination may result in a decrease in the length of time that will be required to bring the entire site into compliance with promulgated groundwater quality standards, but it will do little to speed the attainment of inactive status. Source removal actions are not required at Area D to protect human health and the environment. As discussed in Section 5, no exposure pathway to onsite, offsite, or off-Base receptors currently is complete. No receptor is at risk as a result of potential exposure to site-related contamination. Further, even in the event that an onsite worker were to regularly come into contact with contaminated soil and groundwater at Area D, contaminant concentrations do not pose a potential health threat (i.e., site concentrations do not exceed risk-based soil and groundwater criteria developed for this industrial land use scenario). However, per SDDENR (1994) guidance, mobile LNAPL removal is required for Area D to be considered eligible for inactive status.

The maximum concentrations of BTEX in both groundwater and vadose zone soils have been detected around Building 8215 and the associated fuel transfer lines. Results from the 1994 soil sampling event in the source area indicate that the soil contaminant mass and concentrations are below risk-based cleanup criteria appropriate for an industrial/construction use. However, pockets of mobile LNAPL in the vicinity of MW-6 could continue to be a source of contamination for groundwater at and downgradient from Area D (Sections 6.6.2 and 6.6.3).

Because intrinsic remediation has been effectively reducing dissolved BTEX compounds and naphthalene in the groundwater, and limiting downgradient migration (Section 6), this ongoing remediation process can best be enhanced through a reduction of the continuing source of contamination at Area D. Two candidate source reduction technologies (passive wicking for mobile LNAPL removal and bioventing for residual LNAPL removal), and one contaminant containment and *ex situ* treatment technology (groundwater interceptor trench with aboveground air stripping) have been retained for additional analysis. Three candidate remedial alternatives were developed and are described in the following sections.

8.1.1 Alternative 1 - Additional Leak Testing, Intrinsic Remediation, Long-Term Monitoring, and Land and Groundwater Use Controls

Goal of Alternative 1: Attainment of SDDENR inactive status in approximately 22 years, and compliance with state-promulgated groundwater quality standards at every point in the impacted area in approximately 30 years.

Section 6 presents evidence that groundwater contaminants are being remediated by natural physical, chemical, and biological processes. On the basis of 1994 soil sampling results presented in Section 4 and evaluated in Sections 5 and 6, contaminant concentrations in soils are already below levels that are protective of human health and the environment. Because site subsurface soil contaminants are present at concentrations that do not pose a risk to human health, this site is considered suitable for its current industrial use.

Due to the reported appearance of fresh, unweathered jet fuel in MW-6, additional leak testing of all fuel transfer lines in Area D, particularly lines in the vicinity of MW-6, is recommended. Although LNAPL is not actively removed under this alternative, the small pockets of product suspected to be present at the site do not pose a risk to downgradient receptors. Weathering calculations outlined in Section 6 indicate that COCs will gradually partition from the free product into the groundwater for the next 11 years. At the end of this period of time, provided no fresh LNAPL is introduced into the subsurface, the product will no longer be a significant source of contaminant mass. The Bioplume II model developed for Area D suggests that even if all of the product currently known to exist at Area D is left in place, contaminant concentrations downgradient will stabilize in 20 years and will be removed from the groundwater (to concentrations below promulgated standards) in about 30 years (Figure 6.5). The model also suggests that the plume will not migrate appreciably further than it would if the LNAPL is actively removed. Under this alternative, Area D would be eligible for SDDENR inactive status in approximately 22 years. Approximately 20 years would be required for the plume to stabilize, and an additional 2 years for sampling would be required to demonstrate continued plume stability.

Section 6 provides a thorough evaluation of intrinsic remediation processes operating at the site, and a Bioplume II model was used to simulate the effects of these processes on contaminant mass and mobility over time. The model for this alternative predicted that the existing plume should stabilize by the year 2014, and that all concentrations of groundwater contaminants will be below state groundwater quality standards by the year 2024 (Figure 6.5). Groundwater use restrictions would be put in place until all groundwater impacted by Area D meets state groundwater quality standards. Limitations on groundwater use would not pose additional restrictions on current or planned future land use in this uninhabited industrial area.

This alternative would include annual monitoring of groundwater to verify and document that intrinsic remediation alone is minimizing contaminant mass and

This alternative would include annual monitoring of groundwater to verify and document that intrinsic remediation alone is minimizing contaminant mass and mobility. Natural processes have been removing and should continue to remove contaminant mass and limit contaminant migration. The progress of intrinsic remediation will be monitored using the existing network of monitoring wells. POA wells will be used to ensure that no contaminant concentrations above groundwater quality standards migrate beyond the area of established exposure controls (i.e., an area of restricted groundwater use would be identified). Additional details on the frequency and types of groundwater analysis recommended to confirm intrinsic remediation and to verify the eligibility of the site for inactive status are presented in the long-term monitoring plan included in Section 10.

8.1.2 Alternative 2 - Additional Leak Testing, Mobile LNAPL Removal and Bioventing in Source Area, Intrinsic Remediation, Long-Term Monitoring, and Land and Groundwater Use Controls

Goal of Alternative 2 - Attainment of SDDENR inactive status in approximately 22 years, and compliance with state-promulgated groundwater quality standards at every point in the impacted area in approximately 28 years.

Alternative 2 is similar to Alternative 1 except for the utilization of passive wicking for removal of mobile LNAPL in the vicinity of MW-6 and installation of several bioventing air injection wells in the source area. Bioventing in the source area would be employed to lower residual contaminant concentrations in unsaturated soils in the source area. These actions are not required to protect human health and the environment under the current and most reasonable future land use assumptions for Area D. They are included as a method to more rapidly reduce contaminant mass in the source area. However, time to achieve both inactive status and state groundwater standards would not be appreciably reduced by implementing active source removal activities at the site. Although the mass of contaminants that is introduced into groundwater would be less than estimated under Alternative 1 (i.e., the mass of potential source contaminants would be reduced when mobile LNAPL is removed), the mass of dissolved contaminants already in the groundwater would continue to slowly migrate from the site.

Free-phase product was found in measurable quantities in only one well (MW-6) at the site during all previous investigations. As part of this remedial alternative, all measurable mobile LNAPL would be bailed from the well and a hydrophobic wick would be installed. The wick would absorp any LNAPL flowing into the well. The wick is replaced once it becomes saturated with petroleum hydrocarbons. Wicks are simple to install and do not require modification of either the well or area adjacent to the well.

Bioventing would be used to remediate fuel-related contamination in unsaturated soils at Area D. An *in situ* pilot-scale bioventing test was performed by Parsons ES at Area D in 1993 and 1994. The detailed results of this test are presented in Section 7.2. As the results indicate, bioventing can effectively remove BTEX from unsaturated soils at Area D. Several 4-inch air injection wells were installed in the source area during the field investigation in 1994. Under this alternative, air lines would be run to these wells, and air flow to the wells would be optimized to maximize subsurface biodegradation while minimizing contaminant volatilization. Soil gas flux testing would be performed during system startup to assure that no contaminant vapors are migrating from the subsurface. Figure 8.1 presents the locations of existing bioventing air injection wells that would be used for full-scale bioventing at Area D.

The Bioplume II model developed for Area D was also used to simulate the positive effects of LNAPL removal and bioventing in the source area (details are presented in Appendix E). The anticipated impact of wicking, bioventing, and natural weathering in the source area for 2 years was incorporated into the Bioplume II model by reducing the estimated radius of the mobile LNAPL at the site by 25 percent each year. This approach assumes that 50 percent of the small quantity of LNAPL near MW-6 is recoverable or biodegradable using wicking and bioventing technology and natural weathering. After 2 years of LNAPL reduction, the remaining mass of BTEX was assumed to partition from the residual LNAPL and dissolve into underlying groundwater. Details on these weathering calculations are presented in Section 6.6.2 and Appendix E. Figure 8.2 presents the projected impact of passive wicking, bioventing, and natural weathering on dissolved BTEX concentration and extent of migration over time.

The Bioplume II model for this alternative predicts that the maximum dissolved concentration of total BTEX would be 33 percent less than expected in 5 years if no source removal activity is initiated (i.e., 2,000 µg/L compared to 3,000 µg/L). The total mass of BTEX in the groundwater would be approximately 75 percent of the mass anticipated if no source removal was implemented at the site. However, the beneficial effects of source removal would slowly diminish over time. By the year 2014, the maximum dissolved total BTEX concentration and total BTEX mass in groundwater would be about 88 percent of that anticipated with no source removal. Over time, the effects of LNAPL removal would not appreciably outpace the effects of natural LNAPL weathering and natural contaminant attenuation processes. Hence, if source removal is implemented, the dissolved contaminant plume would stabilize and start to decrease in size after approximately 20 years. Including a 2-year period of verification sampling, Area D would be eligible for SDDENR inactive status in about 22 years under this alternative. Dissolved contaminant concentrations should be reduced below promulgated groundwater quality standards within approximately 28 years.

Land use and groundwater use controls for Alternative 2 would be identical to those described for Alternative 1. Additional site access would be required to maintain the wicking and bioventing systems. Long-term groundwater monitoring also would be the same as Alternative 1, except that additional monitoring of the wicking system would be required to monitor system performance and to quantify mobile LNAPL removal from the groundwater surface. Additional long-term soil gas monitoring and respiration testing also would be required for the full-scale bioventing system to document the amount of contaminant mass being removed from the vadose zone and to ensure optimal system performance.

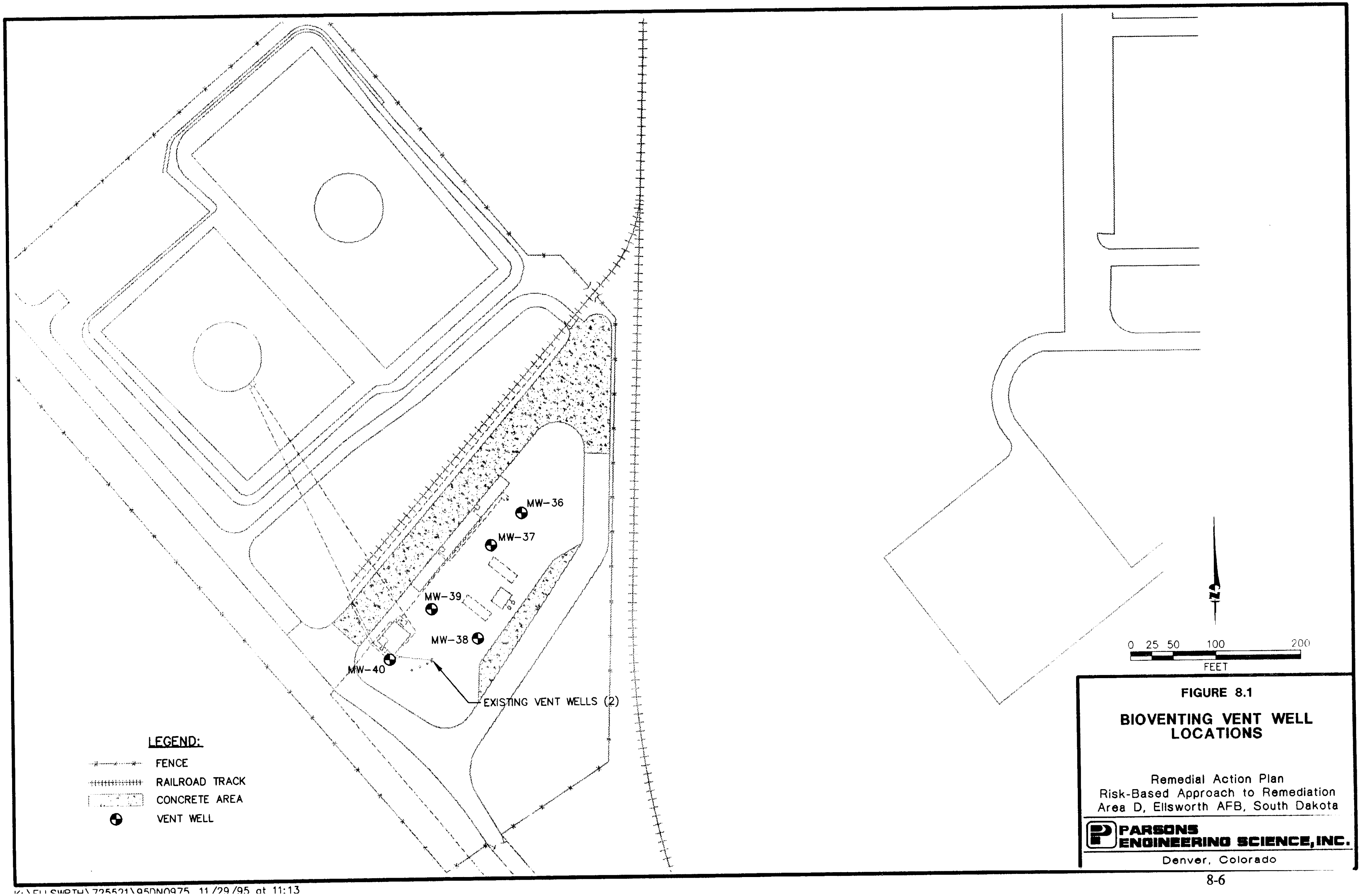

FIGURE 8.1

BIOVENTING VENT WELL LOCATIONS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

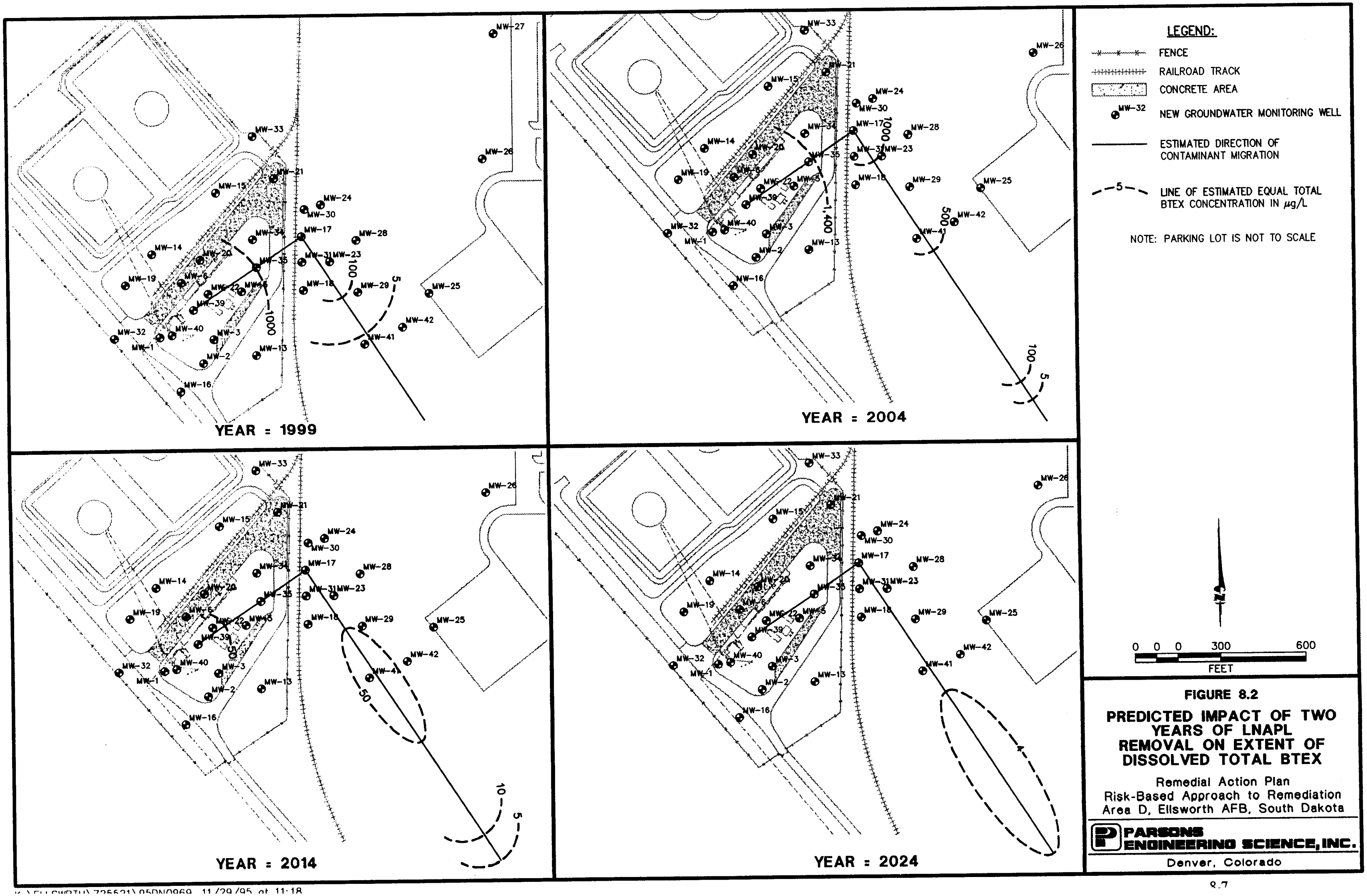

FIGURE 8.2

PREDICTED IMPACT OF TWO YEARS OF LNAPL REMOVAL ON EXTENT OF DISSOLVED TOTAL BTEX

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

8.1.3 Alternative 3 - Additional Leak Testing, Mobile LNAPL Removal and Bioventing in Source Area, Groundwater Extraction via Interceptor Trench, Treatment via Aboveground Air Stripper, Intrinsic Remediation, Long-Term Monitoring, and Land and Groundwater Use Controls

Goal of Alternative 3 - Prevention of additional contaminant migration away from Area D, and compliance with state-promulgated groundwater quality standards at every point in the impacted area in approximately 25 years.

The preceding two remedial alternatives were developed to show that natural chemical attenuation mechanisms, low-cost source reduction technologies, exposure controls, and rational risk management decisions would be sufficient to protect human health and the environment at Area D. Conservative model results suggest, however, that additional downgradient plume migration is anticipated before complete stabilization and eventual destruction is achieved. To prevent additional plume migration at this site, it would be necessary to implement types of remedial technologies different than previously considered. If some level of engineered groundwater remediation is deemed necessary, the site may no longer be eligible for inactive status classification. If such active remediation is desired, inactive status would not be pursued, and the state promulgated groundwater quality standards could be identified as the remedial cleanup goals. Consequently, the objective of this third remedial alternative is different than those of Alternatives 1 and 2, which could significantly affect project timing and costs.

This alternative combines groundwater extraction and treatment with the source removal actions found in Alternative 2. Under this alternative, a passive groundwater interceptor trench would be installed along the downgradient (eastern) edge of the site. The proposed trench location is shown in Figure 8.3. This trench would intercept all contaminated groundwater migrating from Area D. The trench, or french drain, would be constructed along the line formed by groundwater monitoring wells MW-30, MW-17, MW-31, and MW-18. The trench would be approximately 200 feet long, 30 feet deep, and keyed 5 feet into competent Pierre Shale. This will ensure that all groundwater channels emanating from the source area are intercepted. Four groundwater monitoring wells would be used to verify performance of the interceptor trench system. Intrinsic remediation would continue to be the primary removal mechanism for the small mass of contaminants that have already migrated beyond the capture zone of the proposed interceptor trench. An aboveground air stripper would be used to treat extracted contaminated groundwater before its discharge into the sanitary sewer.

Based on estimates of linear groundwater velocity and saturated thickness at Area D (Section 3), the trench would intercept approximately 3,300 gallons of groundwater per day. Groundwater intercepted by the trench would be pumped to the ground surface from a sump at one end of the trench and treated using a tray-type air stripper. After treatment, remediated groundwater would be discharged into a sanitary sewer line running across the field east of Area D. Air stripper effluent sampling would be performed to assure that treated water released from the site meets applicable federal

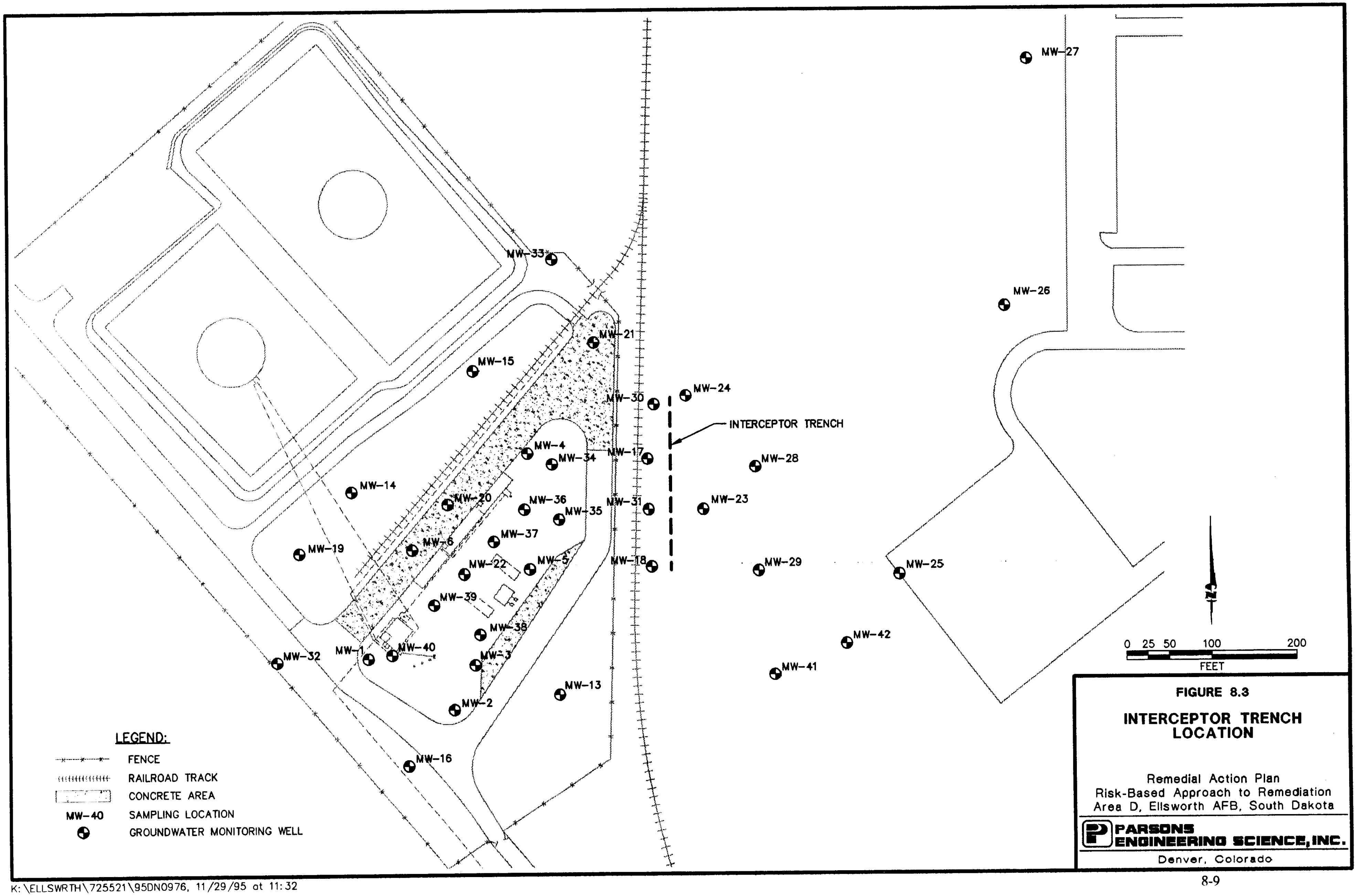

FIGURE 8.3

INTERCEPTOR TRENCH LOCATION

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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and state regulations. Preliminary calculations for the sizing and design of the interceptor trench and associated air stripper are presented in Appendix H.

Land and groundwater use controls similar to those under Alternative 1 are recommended until groundwater contaminants are reduced to concentrations below state groundwater quality standards at all points in the impacted area. During groundwater extraction, long-term groundwater monitoring would continue. Additional monitoring of extracted and treated groundwater would be required to ensure contaminant removal prior to release to the sanitary sewer.

It is anticipated that this alternative of groundwater extraction and source removal could meet state groundwater standards in 25 years. It should be noted that this alternative would not appreciably reduce the amount of time to attain state groundwater standards at every point because dissolved contamination in the source area would not be remediated any faster than under Alternative 2. However, because the plume would be contained by the drain and would not be allowed to migrate any further, the area of land subject to groundwater use controls would be much smaller than under Alternatives 1 and 2. During this time, the wicking and bioventing systems would be operated to meet SDDENR (1994) requirements for the remediation of unsaturated soils and reduction of mobile LNAPL. It is anticipated that 1 year would be required to perform all of the contracting, permitting, and construction required for the installation of the wicking, bioventing, and interceptor trench systems. It is anticipated that 2 years of operation would be required for the wicking and bioventing systems to remove all recoverable mobile LNAPL and to remediate vadose zone soils. The interceptor trench and associated air stripper would be operated until all contaminated groundwater is intercepted and treated. Based on model predictions of contaminant weathering and transport rates, this is estimated to require 25 years.

8.2 REVIEW OF SCREENING AND EVALUATION CRITERIA

The evaluation criteria used to identify appropriate remedial alternatives for soil and groundwater contamination at Area D were adapted from those recommended by the EPA (1988) for selecting remedial actions for Superfund sites (OSWER Directive 9355.3-01). These criteria are consistent with those required for initial screening and detailed evaluation of remedial alternatives by the SDDENR (1994) in Section V of the handbook. These criteria include (1) anticipated effectiveness in meeting target cleanup criteria, (2) technical and administrative implementability, and (3) relative cost. An initial screening of remedial technologies was conducted using the three broad evaluation criteria (Appendix H). The following sections briefly describe the scope and purpose of each criterion.

8.2.1 Effectiveness

Each remedial technology or remedial alternative (which can be a combination of remedial technologies) was evaluated to determine how effectively it can attain the desired degree of cleanup. Remedial technologies that could not cost-effectively attain the desired level of remediation were eliminated from further consideration. The remedial actions proposed for this site under Alternatives 1 and 2 are designed to provide eligibility for inactive status under SDDENR (1994) guidelines. These alternatives proposed for Area D also would eventually remediate groundwater to state groundwater quality standards; however, this is not a remedial requirement to protect human health and the environment. Section 5 provides the rationale for determining that inactive status is appropriate for the site, given the current and planned future land uses and the potential for receptor exposures to site-related contamination. The remedial actions proposed under Alternative 3 are designed to prevent dissolved contamination from migrating downgradient beyond the area of known contamination. Inactive status is not the goal of Alternative 3.

Remedial technologies retained for detailed evaluation are compared in terms of the expected effectiveness of each technology to attain the desired degree of risk reduction at Area D, based on site-specific data supplemented with treatability test data collected for the site. The ability to minimize potentially adverse impacts on surrounding facilities and operations and other environmental resources is considered. Time to implementation and time until protection is achieved are described. Potentially adverse impacts that could be realized during implementation, the cost of necessary mitigation measures, and the potential for residual risks remaining following remedial action also were qualitatively considered. Long-term reliability for providing continued protection, including an assessment of potential for failure of the technology and the potential threats resulting from such a failure, is also evaluated.

8.2.2 Implementability

The technical feasibility, applicability, and reliability of each remedial technology were initially used as broad criteria to narrow the list of potentially applicable remedial approaches for the site. Technologies retained for detailed evaluation were evaluated in terms of engineering implementation, reliability, constructability, and technical/ logistical feasibility. Potential effects due to unanticipated site conditions or significant changes in site conditions were considered. The ability to monitor performance and public perception are discussed. Any prohibition of onsite activities that would be required to ensure successful implementation is described.

8.2.3 Cost

Relative cost of various remedial technologies was used as an initial screening tool (Appendix H). More detailed cost estimates were prepared for each remedial alternative retained for comparative analysis. The cost includes operation and maintenance costs, over the time required for implementation. Present-worth cost estimates were prepared in accordance with OSWER Directive 9355.3-01.

8.3 DETAILED EVALUATION OF REMEDIAL ALTERNATIVES

In this section, each of the candidate alternatives is evaluated using the more detailed criteria described in the previous section. Each alternative is more fully described in terms of its effectiveness, technical and administrative implementability, and cost.

8.3.1 Alternative 1- Additional Leak Testing, Intrinsic Remediation, Long-Term Monitoring, and Land and Groundwater Use Controls

8.3.1.1 Effectiveness

Soil and groundwater sampling performed at Area D in 1994 indicates that concentrations of COCs in both soil and groundwater are below levels that would cause a risk to human health and the environment under an industrial land use scenario. COC concentrations will decrease slowly over time through both destructive and nondestructive attenuation processes. State-promulgated groundwater quality standards should be attained within 30 years. This estimate is based on an assumption that no further releases of fuel will occur at Area D. Prior to implementation of this alternative, the transfer lines at Area D should be pressure tested to rule out the possibility of a continuing source at the site. The assimilative capacity of the saturated media and the site-specific biodegradation rates will be sufficient to eventually transform COCs into carbon dioxide and water and to limit unchecked migration of the plume. It should be noted, however, that the hydrogeology of the site is the primary mechanism responsible for the containment of the plume at the site.

Contaminant mass will slowly partition from mobile and residual LNAPL and dissolve into groundwater. Weathering estimates presented in Section 6.6.2 suggest that mobile LNAPL at the site will no longer be considered a significant source of COC mass in about 11 years. However, this analysis is based on the assumptions that there is a finite amount of fuel in the subsurface at Area D, and that no further releases of fuel will occur. If the amount of LNAPL increases due to a continuing leak or future release of fuel, the partitioning calculation will have to be reevaluated. The Bioplume II model predicts that the dissolved plume will stabilize in approximately 20 years. At that time plume stability can be demonstrated with 2 years of semiannual groundwater monitoring, and inactive status can be attained in accordance with SDDENR (1994) guidance.

Groundwater use controls are an important component of this alternative. The current restrictions of site access (Base perimeter fencing and restricted-area status) provide an effective measure of protection against unauthorized site access and groundwater contact. The present (uninhabited) land use and nonuse of groundwater have effectively eliminated potential current exposure pathways involving groundwater at this site. As a part of this RAP, the Air Force proposes well permit restrictions to prevent withdrawal of groundwater from the shallow aquifer for drinking water applications within 1,000 feet of the leading edge of the current plume until such time as the COCs decrease below state groundwater cleanup standards. Groundwater use restrictions should be a component of any future land use change or property exchange. This strategy will not interfere with the current and intended use of the site as a fueling facility and affected physical media. In the unlikely event that the site is released from government ownership and rezoned for unrestricted residential use within the next 30 years, groundwater use restrictions must be kept in place and enforced until such time as COCs have been reduced to concentrations equal to or below state-promulgated groundwater quality standards at every point.

Long-term groundwater monitoring is recommended under Alternative 1 as a method of measuring the effectiveness of intrinsic remediation and demonstrating the eligibility of the site for inactive status. The groundwater monitoring network would consist of seven existing and four proposed groundwater monitoring wells. For the first 5 years these wells would be sampled annually for BTEX and naphthalene. Sampling details can be found in Section 10, the long-term monitoring plan. Additionally, all wells at the site would be purged and field screened during these annual sampling events to maintain all wells at the site (SDDENR, 1994) and to provide preliminary screening to detect unanticipated releases or transport of contaminants in groundwater at Area D. Based on sampling results, the migration of the contaminant plume will be monitored. The annual sampling strategy would be re-evaluated at the end of the 5-year sampling period. If it appears that the plume is well characterized and moving slowly, sampling would continue every other year. If it appears that the plume is moving rapidly or is not well defined or contained, annual sampling would continue until the plume is well characterized. At that time, samples would be collected every other year. When 3 years of consecutive measurements indicate that the plume has stabilized, analytical sampling will be performed every 6 months over a 2-year period to demonstrate plume stabilization for the attainment of inactive status (SDDENR, 1994). The Bioplume II model for Area D conservatively predicted that it will take 20 years for the plume to stabilize. If conditions warrant, as described above, sampling documentation for the attainment of inactive status may be performed in a shorter amount of time.

It is estimated that inactive status can be achieved at Area D in 22 years under this alternative. Twenty years will be required to achieve plume stability, and an additional 2 years of semiannual verification sampling will be required to satisfy current SDDENR requirements. For the purpose of cost estimation, sampling is assumed to occur annually for the first 5 years, every other year for the next 15 years, and every 6 months for the last 2 years. Based on conservative Bioplume II model predictions, state groundwater standards would be met at the site in approximately 30 years. The cost of annual well purging and screening after the site has attained inactive status is not included in the cost estimate.

A complete long-term monitoring plan is provided in Section 10 to assist the Base in implementing long-term groundwater monitoring. Parsons ES has been retained to complete the first year of groundwater monitoring at Area D. Every year, groundwater data will be compared to model predictions to ensure that intrinsic remediation and site hydrogeology are preventing the contaminant plume from spreading further than predicted by the conservative model. As described above, sampling frequency will be reevaluated after 5 years of sampling. In the event that remediation is not progressing as expected and/or the dissolved plume is migrating further or faster than expected, the following contingency actions are recommended:

- Resample all downgradient sentry and POA wells to confirm initial results;
- Evaluate the results of the most recent groundwater sampling event to determine if there is a trend indicating more rapid contaminant migration due to a lack of intrinsic remediation or misinterpretation of site hydrogeology;

- Complete a risk analysis to determine if the levels of groundwater contamination present a risk given actual site and downgradient land use at the time of sampling; and
- If a significant risk exists, reevaluate more active methods of remediation and implement the most effective risk-reduction method (e.g., the active remediation methods described for Alternatives 2 or 3).

8.3.1.2 Technical and Administrative Implementability

Alternative 1 is technically simple and easy to implement. Four additional groundwater monitoring wells would be required to monitor the area downgradient of the current plume. These wells would be typical groundwater monitoring wells located 800 to 1,200 feet downgradient from the source area at Area D. Several existing wells also are far enough downgradient to serve as POA wells should the plume move to the east. Long-term groundwater sampling is a standard procedure involving minimal worker exposure to contaminated media. Equipment reliability and maintainability are not issues under Alternative 1 because no remediation equipment will be used at the site. The ability of intrinsic remediation and site hydrogeology to reduce contaminant concentrations and limit plume migration would be reevaluated every year.

Administrative implementation of this alternative would require that Ellsworth AFB personnel communicate plans regarding the future use of the Base and Area D to the public and SDDENR. Any proposed change in land use that differs from industrial use, or any proposed groundwater pumping within 1,000 feet of the leading edge of the current plume, should be carefully evaluated. The existing site perimeter fence and controlled-access status also should be maintained to prevent unauthorized access. Any future construction or maintenance activities in this area should be planned to minimize deep excavations (i.e., greater than 10 feet bgs in locations near the source area) and should protect the network of long-term monitoring wells. Wells should remain locked and protected against tampering or vandalism.

Public perception of Alternative 1 could be somewhat negative. Although this alternative would be protective of human health and the environment, contaminants that exceed SDDENR groundwater standards would remain onsite for a lengthy period of time. Recent comments at public hearings related to other remedial actions at Ellsworth AFB have focused on public exposure to contaminants. Because of this, it is anticipated that public reaction to allowing contaminants to persist onsite would not be positive. To counteract potentially negative public opinion, public education would be a prominent part of this alternative and would focus on the site-specific risk analysis and cost savings. No human risk exists at the site, and COC reductions that are compatible with existing and future land use would be achieved at minimum taxpayer expense. Consistent long-term monitoring would provide verification of intrinsic remediation effectiveness and ensure that site conditions do not change over time.

8.3.1.3 Cost

The costs associated with Alternative 1 are presented in Table 8.1. Detailed cost calculations are presented in Appendix H. There would be no remediation equipment operated or maintained under this alternative. Annual costs would include groundwater monitoring and site management (to be provided by Ellsworth AFB), which would include evaluation of annual monitoring data, continued liaison with SDDENR and the public, and participation in future land use planning. Based on the conservative assumption that 22 years of intrinsic remediation and long-term monitoring would be required to pursue and achieve an inactive status classification, the present-worth cost of Alternative 1 is estimated to be $229,130. These costs are most sensitive to unexpected delays in demonstrating plume stability. For example, if 30 years of annual long-term monitoring (30 sampling events) is required to show no increases in concentration or plume size, the present-worth cost of this alternative would increase to $255,980.

8.3.2 Alternative 2 - Additional Leak Testing, Mobile LNAPL Removal and Bioventing in Source Area, Intrinsic Remediation, Long-Term Monitoring, and Land and Groundwater Use Controls

8.3.2.1 Effectiveness

The effectiveness of Alternative 2 in minimizing plume migration and reducing contaminant concentrations at Area D would rely primarily on the mass removal effects of natural biodegradation processes and the limited range of area that can be impacted due to hydrogeologic conditions. LNAPL removal via passive wicking and bioventing would initially reduce contaminant mass in the source area, but would have little effect on the area impacted by dissolved contamination originating from Area D. Intrinsic remediation would be the only remedial approach prescribed for the remediation of dissolved contamination in groundwater at Area D under this alternative.

The Bioplume II model predicts that, even if mobile LNAPL can be efficiently removed from the groundwater surface, the dissolved plume would persist, and the time to achieve inactive status would not be appreciably reduced. Although total contaminant mass would be reduced in the source area as a result of LNAPL removal and bioventing, the Bioplume II model predicts that measurable concentrations would migrate approximately 1,200 feet further downgradient during the next 20 years. The total area of groundwater that could be impacted by the release at Area D would not be significantly different under this alternative than would be expected if no engineered source removal activities were conducted at this site (Section 6.6.3). The Bioplume II model developed for this site is conservative, thus allowing maximum contaminant migration. The major benefit derived from implementing source removal activities at Area D would be the reduction in total contaminant mass that could eventually be released into the environment. It is important to note that even though measurable concentrations are expected in groundwater downgradient from Area D, the model suggests that contaminant concentrations generally would be less than the risk-based remedial criteria presented in Table 5.1. This means that this alternative would be

TABLE 8.1

COST ESTIMATE FOR ALTERNATIVE 1
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Tasks	Capital Costs
Drilling and installation of four groundwater monitoring wells	$25,980
Site Management and Monitoring Tasks	**Annual Costs**
Conduct groundwater sampling at 11 groundwater monitoring wells in accordance with the Long-Term Monitoring Plan (22 years)[a/]	$11,957
Public Education/Liaison (22 years) (assumes 160 man-hours/year)	$9,600
Present Worth of Alternative 1 [b/]	$229,130

[a/] Does not include any activities beyond the attainment of inactive status.

[b/] Based on an annual discount rate of 7 percent.

adequately protective of human health and the environment, even though COC concentrations may be above state groundwater quality standards.

The Bioplume II model for this site predicts that Area D would be eligible for inactive status (due to plume stabilization) in 20 years, and that promulgated groundwater quality standards could be achieved in approximately 28 years. As described for Alternative 1, 2 years of semiannual sampling would be required in years 21 and 22 to demonstrate plume stability.

Bioventing would be employed at Area D under this alternative to remediate unsaturated contaminated soils. This remedial action is not required to protect human health. It is included to satisfy SDDENR's (1994) requirement that all contaminated soils at a site must be remediated to the maximum extent possible before inactive status will be granted. Based on the results of the pilot-scale bioventing test already performed at Area D, bioventing will efficiently and cost effectively remediate fuel-related contamination in unsaturated soils. An average BTEX removal efficiency of 92 percent was documented at the end of 1 year of pilot-scale bioventing system operation. This calculated rate was based on initial and 1-year sampling results at three locations within the pilot test treatment area (Table 7.4).

The groundwater use controls for this alternative would be identical to those described for Alternative 1. The installation and operation of the bioventing system would require additional site access. The long-term groundwater monitoring proposed for Alternative 2 would be identical to Alternative 1, except that the LNAPL removal and bioventing systems would require weekly system maintenance checks and more frequent monitoring to determine the effectiveness of product removal via wicking and BTEX removal via bioventing. Long-term groundwater monitoring requirements would be the same as Alternative 1.

8.3.2.2 Technical and Administrative Implementability

Alternative 2 would require installation of four groundwater monitoring wells as described for Alternative 1, additional site investigation to delineate free product at Area D, and the placement of wicking material in MW-6. Five 4-inch-diameter bioventing air injection wells were installed at Area D during the site investigation in 1994. These five wells and two other wells from the previous pilot-scale bioventing test would be used for full-scale bioventing at Area D. An air injection blower would be installed at the site, and air lines would be trenched to each injection well. Electrical service is available at Building 8215, and the new bioventing blower would be placed in a shed next to the building. All equipment required for both wicking and bioventing can be installed at Area D with a minimal degree of difficulty. All proposed trenching would be across the grass-covered area in the center of the site (Figure 8.1).

As described for Alternative 1, additional drilling would be required for four new downgradient monitoring wells. These new wells and the existing groundwater monitoring wells network would be used for model verification sampling and field screening for fuel hydrocarbon contamination. Several existing wells (MW-25, MW-

26, and MW-27) also are far enough downgradient to serve as POA wells should the plume start to migrate more toward the east from its current southeasterly direction.

The general reliability and maintainability of bioventing systems is high. These are simple mechanical systems. Motors are sealed and do not require lubrication. Air filters provide protection for the air pumps. Filters generally require replacement every 90 to 180 days. Product recovery wicking systems are very simple, do not employ any moving parts, and do not require electrical power. Some types of wicks are reusable, product is mechanically squeezed from the wick and recycled as off-specification fuel. It is estimated that the bioventing and passive wicking systems both would be operational for 2 years to remediate the source area to the maximum extent practical.

Administrative implementation of this alternative would be similar to that described for Alternative 1, and would require that Ellsworth AFB personnel communicate with the public and SDDENR regarding the future use of the site (i.e., continued industrial use). Appropriate land use restrictions must be upheld to prevent unnecessary exposure of humans to contaminated groundwater. Access to the site should continue to be restricted by the perimeter fence and strict access controls. Any future site development plans should protect the bioventing system, the underground piping associated with the system, and the network of long-term monitoring wells. Wells should remain locked and protected against damage.

The public perception of Alternative 2 would be expected to be more positive than Alternative 1. This alternative would be protective of human health and the environment, and could achieve COC reductions at a relatively low expense. Although bioventing and wicking would be expected to more rapidly reduce COC concentrations in the source area, it would have minimal impact on how quickly dissolved contamination downgradient from the source area is eliminated. The primary advantage of Alternative 2 is that it would more fully comply with the source reduction requirements for inactive status based on SDDENR (1994) guidance. No risk currently exists at the site, and COC reductions that are compatible with existing and future land use would be achieved at minimum taxpayer expense. Consistent long-term monitoring would provide verification of intrinsic remediation effectiveness and ensure that site conditions do not change over time.

8.3.2.3 Cost

The costs associated with Alternative 2 are presented in Table 8.2. Detailed cost calculations are presented in Appendix H. Capital costs include the cost of drilling and installation of additional wells and installation of a bioventing injection blower and associated piping. Two years of passive wicking and bioventing operation and monitoring have been included as annual costs. Annual costs also would include groundwater monitoring and site management (provided by Ellsworth AFB), which would include public education, continued liaison with SDDENR, and participation in future land use planning. Sampling and well maintenance costs associated with annual monitoring after inactive status has been achieved are not included in the cost estimate. Using these assumptions, the present-worth cost of Alternative 2 is $304,300.

TABLE 8.2

COST ESTIMATE FOR ALTERNATIVE 2
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Tasks	Capital Costs
Drilling and installation of four groundwater monitoring wells	$25,980
Installation of a passive wick at MW-6	$3,330
Installation of bioventing blower and piping	$33,220
Bioventing confirmation soil sampling	$21,194
Site Management and Monitoring Costs	**Annual Costs**
Conduct groundwater sampling at 11 groundwater monitoring wells in accordance with the Long-Term Monitoring Plan (22 years)[a/]	$11,957
Public Education/Liaison (22 years) (assumes 160 man-hours/year)	$9,600
Operation, maintenance, and monitoring of wicking and bioventing systems (2 years)	$7,680
Present Worth of Alternative 2 [b/]	$304,300

[a/] Does not include any activities beyond the attainment of inactive status.

[b/] Based on an annual discount rate of 7 percent.

Alternative 2 costs are most sensitive to unexpected delays in removing recoverable mobile LNAPL.

8.3.3 Alternative 3 - Additional Leak Testing, Mobile LNAPL Removal and Bioventing in Source Area, Groundwater Extraction via Interceptor Trench, Treatment via Aboveground Air Stripper, Intrinsic Remediation, Long-Term Monitoring, and Land and Groundwater Use Controls

8.3.3.1 Effectiveness

The effectiveness of Alternative 3 in reducing site contaminants to levels below state promulgated groundwater quality standards would depend upon a combination of source removal activities, groundwater extraction and treatment, and long-term intrinsic remediation. Passive wicking and bioventing systems would be installed for source removal as described in Alternative 2. A groundwater interceptor trench would be constructed immediately downgradient from the source area to prevent dissolved contaminants from continuing to migrate away from the source area. The trench would be located just east of the railroad spur that runs along the eastern edge of Area D. The trench which would run along the line formed by groundwater monitoring wells MW-30, MW-17, MW-31, and MW-18 (Figure 8.3), would be approximately 200 feet long and 30 feet deep. The trench would be keyed into competent Pierre Shale to intercept all groundwater flowing away from the source area at the site, including any water that may be flowing on the bedrock in paleochannels. Long-term intrinsic remediation would be used to remediate any dissolved contamination that may have migrated beyond the capture zone of the interceptor trench prior to its construction.

Based on the maximum groundwater velocity for the site and the maximum saturated thickness of the shallow aquifer in the vicinity of the proposed trench, a maximum of 3,300 gallons of groundwater could be intercepted daily (<3 gpm). Water would collect in a sump located at one end of the trench, and would be transferred via piping to the air stripping system using a small submersible pump. Average contaminant load, based on sampling data from wells immediately upgradient from the proposed trench location, is anticipated to be 3.7 mg of BTEX per liter of groundwater extracted, or a maximum of 46 kg of BTEX per day. Groundwater interception, extraction, and treatment would halt the migration of dissolved COCs in the area downgradient from Area D, and also would prevent additional groundwater quality impacts in the event of an accidental subsurface release during future operations.

Groundwater intercepted by the trench would be pumped to the surface and treated using an air stripper. Air stripping has been shown to be very effective for removing volatile contaminants such as BTEX from groundwater. After treatment, groundwater would be discharged into a sanitary sewer line that passes through the field east of the site.

One drawback to the effectiveness of this alternative would be the expected lead time and administrative effort required to design, permit, and construct the groundwater extraction/air stripper treatment system. The installation and operation of a groundwater extraction and treatment system also would require additional site access. The groundwater treatment system would require weekly system checks, and at a minimum, monthly monitoring of groundwater influent and treated effluent groundwater. Bioventing monitoring would be limited to weekly system checks and annual respiration testing to determine the effectiveness *in situ* biodegradation in the contaminated soil. Wicking monitoring would consist of weekly checks and changing fuel-saturated wicks as required.

8.3.3.2 Technical and Administrative Implementability

Alternative 3 would require excavation of approximately 9,100 cubic yards of earth to construct the interceptor trench. The area selected for the trench is outside of the Area D fence, is currently undeveloped land, and has no known utility interferences. Construction should not be constrained by site conditions. The soil to be excavated consists of silty clays, gravels, and fat clays (Pierre Shale). All three soil types are easily excavated with typical earth-moving equipment, and would not present any technical difficulties. The treatment system, including pump and air stripper, would be composed of common remedial equipment that could easily be installed at Area D. Electrical power for the pump and stripper is available at Building 8215. Transmission would involve the installation of several power poles or underground cable. For this engineering estimate, it was assumed that this treatment system would be installed inside a prefabricated building, which would be heated during winter operations.

Submersible pumps and air stripping systems generally are highly reliable when they are properly maintained. The most frequent reliability problems occur with pump controls, which must be carefully set to minimize pump cycling. Due to the long (i.e., 25-year) operating period, the submersible pump would probably have to be replaced an estimated five times over the life of the extraction system. Weekly monitoring of the system would be required to assure proper operation. The most significant maintenance requirement for this system would be regular monitoring of the stripper effluent to ensure that discharge standards are attained. The analytical requirements and documentation associated with meeting sanitary sewer discharge specifications could add appreciably to the monthly operation and maintenance costs.

The passive wicking and bioventing systems would be installed and operated for 2 years, as described for Alternative 2. Seven existing bioventing wells would be plumbed to a single injection blower. The air injection blower would be installed in a shed adjacent to Building 8215. Periodic maintenance would be required for both systems, as described for Alternative 2.

The same groundwater monitoring well network described in Alternative 1 would be necessary to monitor the natural attenuation feature of Alternative 3. Monitoring of four additional groundwater wells would be necessary under Alternative 3 to verify the effectiveness of the interception trench system. The network of long-term monitoring wells for Alternative 3 would consist of a total of 15 groundwater monitoring wells.

Administrative implementation of this alternative would require that Ellsworth AFB continue to communicate with SDDENR and the public regarding the future use of Area D. The perimeter fence and controlled site status should be maintained to prevent unauthorized entrance. Any future land use plans should protect the interceptor trench, groundwater treatment, wicking, and bioventing systems and network of long-term monitoring wells. Wells should remain locked and protected against tampering.

Public perception of Alternative 3 would be expected to be positive. However, most experienced remediation professionals would view this level of treatment as excessive, given that the site is zoned for uninhabited industrial use and the risk of offsite contaminant migration and receptor exposure is very low. This alternative would be protective of human health and the environment, and would achieve COC reductions that are compatible with current industrial land use. However, any benefits of more rapid risk reduction may not be justified, given the additional cost.

8.3.3.3 Cost

The costs associated with Alternative 3 are presented in Table 8.3. Detailed cost calculations are included in Appendix H. Capital costs include the cost of design and construction of the groundwater interceptor trench and the wicking and bioventing systems. Annual costs would include 2 years of wicking and bioventing, 25 years of groundwater monitoring and site management to demonstrate plume containment and reductions in contaminant levels, and 25 years of operation and maintenance of the groundwater interception and treatment system. Based on these assumptions, the present worth cost of Alternative 3 is $1,116,300. Alternative 3 costs are most sensitive to additional years of groundwater treatment system operation and maintenance.

8.4 RECOMMENDED ALTERNATIVE

Alternative 2 (Additional Leak Testing, mobile LNAPL Removal, Bioventing, Intrinsic Remediation, Long-Term Monitoring, and Groundwater Use Controls) is recommended for remediation of Area D based on its expected effectiveness in attaining inactive status and state-promulgated groundwater standards, its relative simplicity with respect to technical and administrative implementation, and its relatively low overall cost. Table 8.4 provides a summary of the evaluation process for each alternative.

The conservative Bioplume II model suggests that the addition of LNAPL wicking and bioventing in the source area could reduce the total mass of contaminants that could be introduced into the groundwater over time at Area D. As discussed in Section 7 and summarized in this section, there is considerable evidence that bioventing will effectively reduce fuel-related contamination in unsaturated soils in the vicinity of the source area at Area D. In accordance with SDDENR guidance, bioventing will be implemented in seven injection wells to remediate contaminated soils to the maximum extent possible.

Significant evidence exists that natural physical, chemical, and biological conditions at Area D will limit the migration of the dissolved contaminant plume. Currently, the dissolved plume extends approximately 530 feet downgradient from the source area at Area D. Based on the conservative Bioplume II model, the plume is expected to

TABLE 8.3

COST ESTIMATE FOR ALTERNATIVE 3
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Tasks	Capital Cost
Design and construction of a groundwater intercept trench	$439,320
Drilling and installation of four groundwater monitoring wells	$25,980
Installation of a passive wick at MW-6	$3,330
Installation of bioventing blower and piping	$33,220
Bioventing confirmation soil sampling	$21,194
Site Management and Monitoring Costs	**Annual Costs**
Conduct groundwater sampling at 15 groundwater monitoring wells in accordance with the Long-Term Monitoring Plan (25 years)	$13,117
Public Education/Liaison (25 years) (assumes 160 man-hours/year)	$9,600
Operation, maintenance, and monitoring of wicking and bioventing system (2 years)	$7,680
Operation, maintenance, and monitoring of groundwater intercept trench and treatment system (25 years)	$15,120
Present Worth of Alternative 3 [a/]	$1,116,300

[a/] Based on an annual discount rate of 7 percent.

TABLE 8.4
SUMMARY OF REMEDIAL ALTERNATIVE EVALUATION
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Remedial Alternative	Effectiveness	Implementability	Present Worth Cost Estimate
Alternative 1			$229,130
-Additional Leak Testing -Intrinsic Remediation -Long-Term Monitoring -Land and Groundwater Use Controls	Contaminant mass, volume, and toxicity will gradually be reduced by intrinsic remediation alone. SDDENR (1994) criteria for inactive status will be met in approximately 22 years.	Technically simple and easy to implement. Long-term groundwater monitoring for 22 years is required. Groundwater use restrictions need to be implemented and would not incur any additional land use restriction beyond those currently in place at Area D. Requires public education.	
Alternative 2			$304,300
-Additional Leak Testing -Bioventing and Wicking in Source Area (2 years) -Intrinsic Remediation -Long-Term Monitoring -Land and Groundwater Use Controls	Similar to Alternative 1, with the addition of bioventing and passive wicking to increase contaminant removal and degradation in the source area. SDDENR (1994) criteria for inactive status will be met in approximately 22 years. Pilot testing indicate bioventing will significantly remove BTEX compounds from unsaturated soils. Wicking has not yet been tested at Area D, but is expected to be effective for recovering any LNAPL and remediating contaminated soils and groundwater.	Long-term groundwater monitoring for 22 years is expected. The bioventing and wicking systems are expected to operate for 2 years. This systems will require weekly monitoring. Groundwater and land use restrictions would be the same as Alternative 1. Positive public perception.	
Alternative 3			$1,116,300
-Additional Leak Testing -Bioventing and Wicking in Source Area (2 years) -Groundwater Extraction and Treatment -Intrinsic Remediation -Long-Term Monitoring -Land and Groundwater Use Controls	Similar to Alternative 2, with the addition of groundwater removal and treatment. SDDENR (1994) criteria for inactive status will be met in approximately 25 years. Groundwater use restrictions are more limited than Alternatives 1 and 2, but limited land use restrictions may be necessary to protect the interception trench.	Long-term groundwater monitoring and operation of the interception trench/treatment system for 25 years is expected and will require weekly monitoring. A discharge permit will be required for discharge of treated groundwater to the sanitary sewer. Lengthy lead time required for design and installation of groundwater interception trench. Positive public perception.	

migrate approximately 1,200 feet downgradient from the source area at detectable concentrations before it begins to recede. In accordance with SDDENR (1994) guidance, the site may be eligible for inactive status once annual monitoring demonstrates no significant increases in contaminant concentrations and no appreciable horizontal migration over time. The Bioplume II model conservatively predicts that under Alternative 2, the plume emanating from Area D will stabilize in size by the year 2014. It is important to note that the concentration and total mass of dissolved contaminants will be continually reduced by natural destructive attenuation processes. Due to the conservative nature of the Bioplume II model, the site may actually be eligible for inactive status classification sooner than anticipated.

Given the current and projected industrial land use at Area D and in surrounding areas, no active remediation is required at this site to protect human health or the environment; passive wicking and bioventing are proposed to accelerate attainment of inactive status for the site. Conservative Bioplume II modeling predicted limited plume migration, with virtually no chance of off-Base migration. Long-term groundwater monitoring will be used to verify the effectiveness of intrinsic remediation and to assure that COCs do not migrate beyond the area under reliable exposure controls. Limitations on groundwater pumping at this site should not affect future land use or operations.

Although Alternative 3 could limit future plume migration, the cost of constructing and maintaining an interception trench and aboveground treatment system at this site is not justified given that no current risk exists, no future risk is expected, and no off-Base contaminant migration is possible. Alternative 3 could be implemented if downgradient land use required more immediate groundwater use.

On the basis of this evaluation, Alternative 2 provides the best combination of risk reduction and low cost without imposing additional land use restrictions. Section 9 provides additional details on the recommended implementation of this alternative.

SECTION 9

IMPLEMENTATION OF RECOMMENDED REMEDIAL ACTION

This section provides an implementation plan for the recommended remedial action Alternative 2 (mobile LNAPL removal and bioventing in the source area, intrinsic remediation, long-term monitoring, and land and groundwater use controls) at Area D. This section reviews the scope and schedule of remediation activities, discusses possible contingencies if this remedial approach does not prevent offsite migration of COCs, and summarizes costs by fiscal year.

9.1 SCOPE OF REMEDIAL ACTIVITIES

The recommended remedial action alternative will be implemented over a 22-year period to ensure that Area D is eligible for inactive status classification in accordance with SDDENR (1994) guidance. The following sequence of events is proposed to fully implement this remedial action.

9.1.1 Review and Approval of Remedial Action Plan

Approval of this draft RAP is within the authority Ellsworth AFB personnel, SDDENR, and EPA Region VIII. This group of environmental professionals is responsible for review of this draft RAP and eventual implementation of the approved remedial actions. Copies of this document will be distributed to each of the above organizations for review and comment. Approximately 30 days has been designated in the implementation schedule for review of the document.

Following the 30-day review period, a project presentation will be provided by Parsons ES and AFCEE at a location selected by Ellsworth AFB, SDDENR, and EPA personnel. The purpose of this presentation will be to describe the major findings of this risk-based remediation project and to receive feedback and discuss any unresolved issues that may surface during document review. This direct interface between the document preparers and the group charged with RAP implementation is essential for final RAP preparation and a smooth transition into remedial actions.

Following the presentation, any unresolved issues or concerns can be provided in writing to AFCEE and/or Parsons ES for additional discussion and formal incorporation into the final RAP. Parsons ES will have approximately 30 days to produce a final RAP and forward it to Ellsworth AFB for implementation.

9.1.2 Tank and Transfer Line Leak Testing

Prior to the implementation of any of the recommended engineered remedial actions or any of the monitoring programs at Area D, all tanks and transfer lines in the fuel yard should be leak tested. Chemical analysis of an LNAPL sample recently collected from MW-6 has indicated that the free product found at the site is fresh and unweathered. This indicates that a small, continuous leak may be present at the site. Testing must be performed to rule out this possibility or correct this situation prior to the implementation of the remedial action plan. After testing is performed and the possibility of active leaks has been ruled out, remedial activities at Area D can begin.

9.1.3 Design and Installation of Full-Scale Bioventing System in Source Area

Parsons ES has been contracted by AFCEE to construct a full-scale bioventing system at Area D, and as part of this remedial action, Parsons ES is responsible for system construction and start-up. Ellsworth AFB personnel will be responsible for long-term operation and maintenance (O&M). Seven existing bioventing wells at Area D will be plumbed and connected to a Gast® R6 regenerative blower located in a shed adjacent to Building 8215. Well locations are shown in Figure 8.1. Wells are placed to allow for maximum oxygenation of the subsurface based on an effective radius of influence of 30 feet (Section 7.3.3). The existing 4-inch-diameter VWs are screened across the interval of unsaturated soil contamination in the source area at Area D, generally 10 to 25 feet bgs. Each well will be individually piped and valved to control air flow into each well. Injection rates will be optimized for each well to maximize biodegradation potential while minimizing contaminant volatilization. Soil gas flux testing will be performed before and immediately after system startup to assure that contaminant vapors are not being forced out of the subsurface by air injection.

After system startup and optimization, periodic monitoring of the system will be performed. Every 2 weeks the system will be monitored by Ellsworth AFB personnel to assure proper operation. Blower temperature and injection pressure will be recorded, and the inlet air filter will be changed as necessary. Once each year, *in situ* respiration testing and soil gas sampling will be performed by Parsons ES to assess biodegradation rates at Area D. At the conclusion of approximately 2 years of operation, confirmatory soil samples will be collected by Parsons ES to determine contaminant reduction. If soil BTEX levels have been significantly reduced, the bioventing system will be deactivated. Based on results from the pilot test performed at Area D, fuel-related compound concentrations in contaminated soils at Area D should be reduced to the maximum extent practicable, per state regulations for petroleum-contaminated soils and SDDENR (1994) guidance, after 2 years. Additional details on confirmatory sampling and system operation and maintenance requirements are provided in Section 10, the long-term monitoring plan for Area D, and in Appendix I, the SAP.

9.1.4 Installation of Passive Wicking System in Source Area

A passive wicking system is proposed for mobile LNAPL recovery at Area D. A contract to install a mobile LNAPL recovery system at Area D has not yet been awarded. However, FMG, Inc. has been contracted to design a free-product removal system. Parsons ES recommends that Ellsworth AFB and FMG, Inc. carefully examine the merits of wicking technology. The following information is provided as a discussion of the recommended remedial technology for the removal of LNAPL at Area D.

Based on current data, it appears that the area of mobile LNAPL at Area D is limited and concentrated around MW-6. An LNAPL baildown and recovery test performed at the site in October 1995 indicated that product recovery in the well is very slow (Table 7.1). Passive wicking could be used to absorb product as it slowly collects in the well. It is suggested that a Peatwick™ passive wick (Environmental Basics Company, 610-796-9102) be suspended in MW-6 for LNAPL recovery. To install the wick, all recoverable product would first be hand bailed from the well and disposed of as off-specification fuel. After all recoverable LNAPL is removed from the well, a Peatwick™ canister containing a hydrophobic wick would be placed in the well. The wick, consisting of hydrophobic, dehydrated peat moss, would be placed so that the bottom of the wick is at the LNAPL water interface. Further details on the Peatwick™ are provided at the back of Appendix H. As LNAPL recovers in the well, it will be preferentially absorbed by the peat moss wick. The canister required no power supply and would be simply hung in the well with nylon rope. Additionally, no other external connections are required, and the existing flush-mount cover can remain in place.

O&M requirements for the wicking system would be very minimal. Wick systems have no moving parts and required no electricity. The wick will have to be removed and replaced periodically. The length of time between wick replacements would be determined during the first few weeks of operation. Every 2 weeks, the wick will be removed and inspected. If the wick is saturated, it can be easily replaced with an inexpensive ($15) replacement wick. This inspection would be performed by Ellsworth AFB personnel in conjunction with the weekly bioventing system check. One wick will absorb approximately 1 gallon of petroleum hydrocarbons. It is anticipated that the wick in MW-6 will have to be replaced once each month. Saturated wicks can be disposed of through incineration; the peat moss is fully combustible. According to the manufacturers specification, the wicks will burn with a residual ash residue of less than 5 percent. Mobile LNAPL thicknesses in groundwater monitoring wells within the source area at Area D will be measured annually. When it appears that no measurable levels of LNAPL remain on the groundwater surface and no additional product is being recovered, the wicking system will be deactivated. Based on the limited amount of LNAPL currently found at Area D, it is estimated that the wicking system could remove all recoverable free-phase product from the soils near MW-6 in less than 2 years. Additional details on system O&M requirements are presented in Section 10, the long-term monitoring plan.

9.1.5 Implementation of Long-Term Groundwater Monitoring

Section 10 of this RAP provides a complete long-term monitoring plan (LTMP) for Area D. Long-term groundwater monitoring is essential for verification of intrinsic remediation progress and confirmation that natural processes are retarding plume migration. Prior to implementation of long-term monitoring, four additional groundwater monitoring wells will be installed at the site. One well will be installed approximately 350 feet downgradient from the current leading edge of the dissolved contaminant plume. This well will be monitored to assure than plume migration and contaminant concentrations are progressing as predicted by the Bioplume II model of the site. The three remaining wells will be installed approximately 1,200 downgradient from Area D and will serve as POA wells. These three wells will be used to demonstrate plume stability. The wells will be located at the maximum downgradient edge of the plume predicted by the model for the site. If contaminant concentrations in wells located within the plume have stabilized and the three POA wells are free of site-related contaminants, it can inferred that the plume has stabilized. Based on modeling predictions, site-related contaminants should never be detected in the POA wells at concentrations exceeding state groundwater quality standards. If groundwater contaminants attributable to activities at Area D are detected at concentrations above state standards in the POA wells, contingency actions outlined in Section 9.3 will be implemented. No other additional wells will be required at Area D to facilitate the monitoring of contaminant migration at the site.

Careful implementation of the LTMP is a key component of this RAP. The proposed remedial alternative for this site calls for annual groundwater sampling at all groundwater monitoring wells at the site for the first 5 years. After 5 years of annual sampling, the sampling strategy will be reevaluated. If plume migration is slow, sampling frequency will be decreased to every other year. Wells will be purged in accordance with the SAP presented in Appendix I and then sampled for BTEX and naphthalene. Annual sampling of all wells will be used to verify the nature and rate of plume migration and to assure that there are no future releases of petroleum hydrocarbons at the site. After three consecutive sampling events indicate that the plume is not migrating any further, analytical sampling will be performed semiannually for an additional 2 years. These 2 years of semiannual sampling will be used to meet the sampling requirements specified by SDDENR (1994) to attain approval for inactive status. The results of the conservative Bioplume II model developed for the site predicted that the plume will stabilize in approximately 20 years if LNAPL recovery and bioventing are implemented in the source area. If the plume migrates as predicted, semiannual sampling to document plume stability for the attainment of SDDENR inactive status would occur in years 21 and 22. Accordingly, 17 sampling events have been estimated for implementation of Alternative 2 (i.e., annual sampling for 5 years, biannual sampling for 15 years, and semiannual sampling for 2 years). Because the model is conservative and the site hydrogeology is difficult to characterize, the actual time required for the plume to stabilize may be significantly less than the predicted 20 years. If it appears that the plume has stabilized at any point during the planned annual sampling period, the 2-year, semiannual analytical sampling program will be implemented. Additional details on analytical sampling can be found in the LTMP in Section 10 and the SAP in Appendix I.

Annual groundwater monitoring is recommended to begin in April 1996. Annual monitoring is considered appropriate given the limited contaminant migration observed from 1992 to 1994. Parsons ES is under contract to complete the April 1996 sampling event. During this event, 11 long-term monitoring wells will be sampled for analytical analysis of COPCs. Additional details are provided in Section 10, the LTMP. The number of years that annual groundwater monitoring is required will be based field screening results, as discussed above.

Contaminant biodegradation and transport calculations presented in Section 6 suggest that benzene and naphthalene concentrations in groundwater should gradually be reduced below state groundwater cleanup criteria in approximately 28 to 30 years. However, classification of Area D as an inactive-status site is the primary goal of this remedial action and groundwater monitoring plan. Compliance with state-promulgated groundwater standards is not the intent of the recommended action. Groundwater monitoring results will be provided to SDDENR and EPA Region VIII to apprise all parties involved on remediation progress and to provide new information for pending land use decisions, as necessary.

9.1.6 Verification of Current and Future Land and Groundwater Use Controls

An important element of the recommended remedial action at Area D is groundwater use control. On the basis of 1994 groundwater data and the exposure pathways analysis in Section 5, the site is immediately acceptable for continued industrial use provided that future land use does not require extraction of site groundwater for potable use. It is recommended that the current restricted access be maintained at the site, and that any future land use plans for Area D and impacted environs stipulate that shallow groundwater will not be extracted within 1,000 feet of the leading edge of the current dissolved plume until COPC concentrations have been reduced below state groundwater quality standards. Excavation in the plume area also should be limited to depths of less than 10 feet bgs. These minor restrictions will eliminate potential receptor exposure points for contaminated soils and groundwater.

9.2 IMPLEMENTATION SCHEDULE

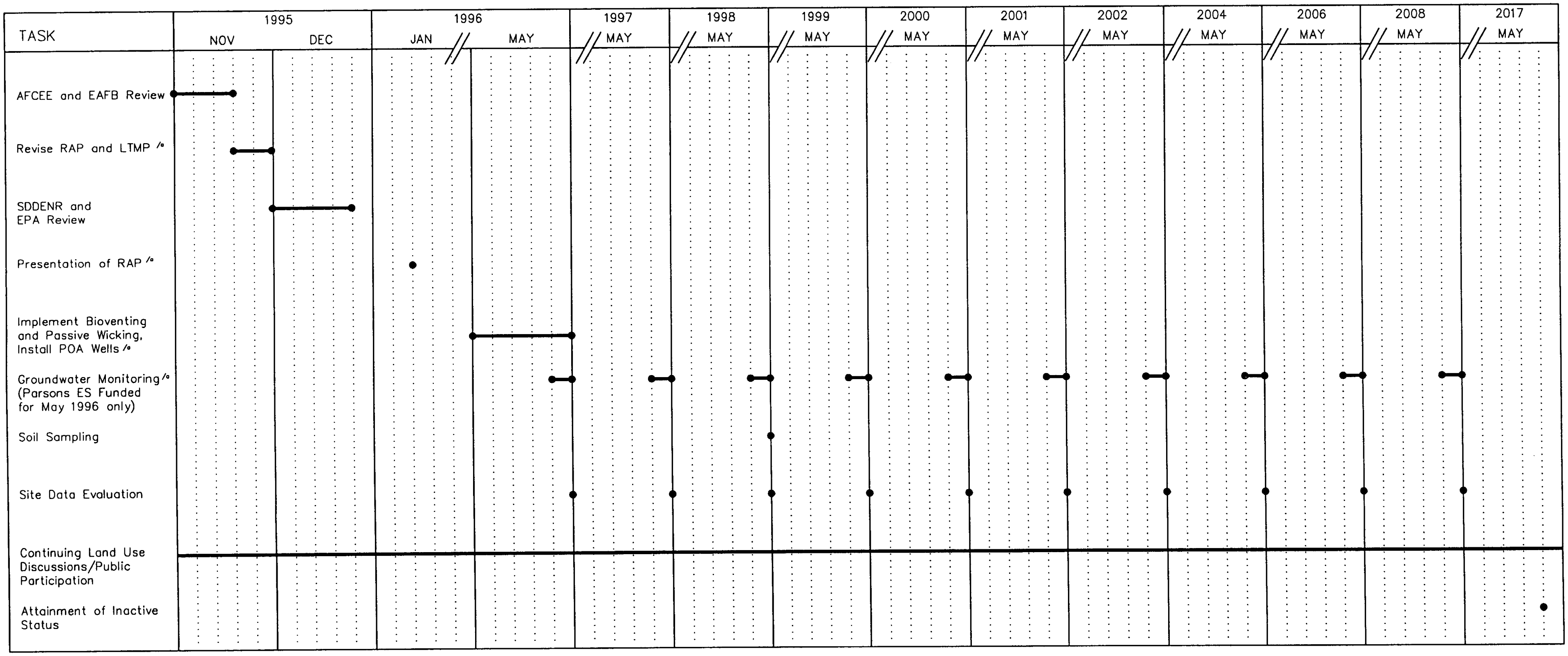
Figure 9.1 is a proposed schedule for implementation of the RAP at Area D. The schedule is provided for planning purposes only, and is subject to approval of the RAP by Ellsworth AFB and SDDENR. The schedule has significant flexibility at this point because under the current land use and proposed future land use, site contaminants pose no risk to human health or the environment. The only action required in the near term is leak testing of all lines and tanks at Area D to ensure that a continuing source of contamination does not exist at the site. The only potential schedule delay that could occur would result from a lack of funding to complete leak testing or source reduction actions. Parsons ES has already been contracted by AFCEE for the design and installation of the full-scale bioventing system for remediation of vadose zone soils at the site. FMG, Inc. is under contract to design and implement a product recovery system.

9.3 CONTINGENCY PLAN

Should intrinsic remediation prove to be an ineffective means to reduce contaminant concentration, mass, and mobility in groundwater at Area D, there should be no impact on the land use plans for this area. No new land use has been proposed for Area D or the surrounding area. For the foreseeable future, Area D will continue to operate as an

FIGURE 9.1

IMPLEMENTATION OF REMEDIAL ACTION PLAN
LONG-TERM MONITORING PLAN
AREA D, ELLSWORTH AFB, SOUTH DAKOTA



/a Activity will be performed by Parsons ES.

active fuel storage and dispensing area in support of aircraft operations at Ellsworth AFB. Groundwater extraction in this area is not anticipated so long as alternate water supplies exist. In the event that shallow groundwater near this site must be extracted for potable uses, and state groundwater standards have not yet been achieved, the following contingency actions are available:

- The results of the most recent groundwater sampling event will be evaluated to determine if there is a trend indicating that intrinsic remediation is not proceeding at the rates predicted in Section 6.

- A risk analysis will be completed to determine if levels of groundwater contamination present an actual risk based on the intended use of the groundwater.

- If significant risk exists, more active methods of remediation will be evaluated. This could include possible initiation of active remediation methods described for Alternative 3 (Section 8).

Once again, failure of intrinsic remediation of achieve SDDENR (1994) cleanup criteria will not impact the approved use of this area as a fuel operations area, unless groundwater must be extracted for long-term potable industrial uses. Contingency plans also would be required if the plume continues to migrate toward the southeast at concentrations exceeding SDDENR (1994) cleanup criteria. Three POA wells will be installed approximately 1,200 feet downgradient from the site to assure that contaminants do not migrate further than predicted by the Bioplume II model. If COCs are detected at concentrations significantly beyond model predictions in any of the long-term monitoring wells, or if annual groundwater sampling indicates a significant change in the direction of plume migration, the following contingency actions are available:

- If a POA well appears to contain COC concentrations exceeding state groundwater standards, a second sample will be collected to confirm that analytical results are above state standards.

- All downgradient POA wells will be sampled to determine the extent of plume migration and to locate the centerline of the leading edge of the plume.

- The results of the most recent groundwater sampling field screening event will be evaluated to determine if there is a trend indicating that intrinsic remediation is not proceeding at the rates predicted in Section 6.

- A risk analysis will be completed to determine if concentrations approaching the POA well present a risk based on the actual intended use of the groundwater.

- If significant risk exists, or if COC concentrations exceeding state groundwater cleanup criteria could migrate beyond the area of exposure control, more active methods of remediation will be evaluated. This could include possible initiation of active remediation methods described in Alternatives 3, including a groundwater extraction system designed to halt the migration of contaminants beyond the POA.

9.4 COST OF IMPLEMENTATION

A summary of the estimated present worth cost of implementing the recommended remedial alternative is provided in Section 8.3.2.3. Table 9.1 provides a cost estimate, based on expenditures in the next 5 fiscal years, to assist the Air Force in budgeting for Area D remedial actions. As discussed in Section 8.3.2.3, this cost estimate is most sensitive to the number of years of long-term monitoring required.

TABLE 9.1

ESTIMATED COST BY FISCAL YEAR[a]

REMEDIAL ACTION PLAN

RISK-BASED APPROACH TO REMEDIATION

AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Task	FY96	FY97	FY98	FY99	FY00
Annual Groundwater Sampling[b]	$11,957[c]	$12,555	$13,183	$13,842	$14,534
Bioventing and Wicking Capital Cost	$ 3,330[c]				
Drill/Install Four Additional Groundwater monitoring wells	$25,980[c]				
Bioventing and Wicking Operation and Maintenance	$7,680	$8,064			
Soil Sampling in Source Area (After 2 years of operations)			$24,266		
Site Management (By EAFB)[b] (160 hours/year)	$9,600	$10,080	$10,584	$11,113	$11,669
Fiscal Year Totals	$58,547	$30,699	$48,033	$24,955	$26,203

[a] Estimates for the first 5 years of a 22-year long-term monitoring plan.

[b] Assumes a 5 percent annual inflation rate.

[c] Activity to be performed by Parsons ES.

SECTION 10

LONG-TERM MONITORING PLAN

10.1 OVERVIEW

In keeping with the requirements of the recommended remedial action for Area D (mobile LNAPL recovery and bioventing in the source area, intrinsic remediation, long-term monitoring [LTM], and land and groundwater use controls), an LTMP has been developed. This LTMP includes O&M and sampling requirements for the proposed wicking and bioventing systems, a proposed groundwater monitoring network, sampling and analysis strategies for groundwater, and an evaluation of land use controls. A schedule for implementation of the actions described in the plan is presented in Figure 9.1. The purpose of LTMP is to confirm the effectiveness of engineered source removal technologies and natural processes at reducing contaminant concentration, mass, mobility, and toxicity in affected media. This plan also will assess site conditions over time and the need for additional remediation.

As part of LTM, contaminant behavior in groundwater over time will be monitored to verify that the proposed remedial action is sufficient to protect human health and the environment. The areal extent of contamination will be monitored for increases in concentration and spatial distribution of the COCs during the course of the proposed remediation. In the event that data collected under this LTM program indicate that engineered source removal technologies and natural physical, chemical, and biological processes are insufficient to achieve inactive status for Area D, contingency actions will be implemented to augment the effects of the proposed remedial action.

10.2 PASSIVE WICKING OPERATION AND MAINTENANCE

Under the recommended remedial alternative, a hydrophobic wick will be placed in MW-6 to recover any LNAPL entering the well. During operation, checks will be made twice a month to assure that the wick is still absorbing LNAPL and the wick has not become completely saturated with hydrocarbons.

All maintenance activities will be recorded on an O&M checklist and will become part of the site record. In addition to the bimonthly monitoring described above, mobile LNAPL levels in MW-6 will be measured annually by Parsons ES. Results from these assessments will be used to determine when all recoverable LNAPL has been removed from the groundwater surface. Once measurable levels of mobile LNAPL are no longer evident in any well for at least two consecutive monitoring events, the wick will be removed from the well. Based on estimates of the amount of LNAPL present in the subsurface at Area D, it is predicted that all recoverable product near MW-6 (estimated at 50 percent of the total release) will be removed in 2 years or less using the proposed product recovery technology.

10.3 BIOVENTING SYSTEM OPERATION AND MAINTENANCE

After all air injection wells have been plumbed, and air flow through the system has been optimized, long-term operation will begin. An O&M manual will be prepared and presented to Ellsworth AFB personnel prior to the beginning of long-term operation. Parsons ES will prepare the manual as part of system installation. Contents of the O&M plan for bioventing will be very similar to documentation prepared for the wicking system. System as-built drawings, vendor specifications, schematic drawings, maintenance checklists, replacement parts and suppliers, and a list of emergency contacts will all be included in the bioventing O&M manual.

System checkups will be performed every other week by Ellsworth AFB personnel. The following activities will typically be performed during a bioventing system check:

- Record air injection pressures and flow rates at each of the injection wells;
- Measure injection blower operating temperature and inlet vacuum;
- Assess the condition of the air inlet filter element and replace as necessary; and
- Note any unusual operating characteristics (e.g., clogged lines or tripped breakers).

All maintenance activities will be recorded on an O&M checklist and will become part of the site record.

In addition to the monitoring described above, *in situ* respiration tests will be performed annually by Parsons ES at all injection vent wells (VWs) and at the discrete vapor monitoring points (MPs) installed as part of the previous bioventing pilot test at the site. Soil gas samples collected from these locations will be analyzed for BTEX and TVH. This testing and sampling will be used to assess remedial progress and to assure that biodegradation is continuing in accordance with bioventing technical protocol (Hinchee *et al.*, 1992). If at the end of 2 years of operation it appears that the majority of the BTEX contamination at the site has been biodegraded based on respiration rates and soil gas samples, confirmatory soil samples will be collected. Samples will be analyzed for BTEX by USEPA Method SW8020 and for TEH/TVH by USEPA Method SW8015. Additional sample collection and analysis details for soil and soil gas are presented in Section 10 and Appendix I, the SAP. Soil samples will be compared to initial samples collected during VW installation and used to determine if contaminant levels have been remediated to the maximum extent practical. Soil gas samples will be used in the same manner. Based on the results of the pilot test performed at Area D, 2 years of operation should be adequate to reduce compound-specific soil contaminants in saturated soils to levels approaching analytical method PQLs. When confirmatory soil samples indicate that unsaturated soils have been remediated to the extent practicable (SDDENR, 1994), the bioventing system will be deactivated. Air injection VWs will continue to serve as groundwater monitoring wells after system deactivation.

10.4 GROUNDWATER MONITORING NETWORKS

A total of 11 wells will be used to monitor dissolved contaminant removal and migration at the site over time. These wells are located within, upgradient from, downgradient from, and at the leading edge of the dissolved contamination to ensure that natural attenuation processes are occurring at rates sufficient to remove COPC mass and minimize contaminant transport in groundwater. The locations of all wells to be used for long-term monitoring are illustrated in Figure 10.1.

10.4.1 Upgradient and Plume Wells

One existing well (MW-32), which is upgradient from and outside the influence of the contaminant source, will be monitored to evaluate background conditions. Five additional wells located within or at the lateral edge of the dissolved contaminant plume area will be monitored to evaluate the rates of contaminant removal as a result of source removal and natural attenuation. Wells located at the lateral edges of the plume will be monitored to assure that future plume migration follows the same flow patterns that have caused the current contaminant distribution at the site. One of the plume wells (MW-6) is located in the source area, whereas the other two plume wells (MW-21 and MW-29) are located downgradient from the source area in the dissolved contaminant plume. Finally, two wells (MW-17 and MW-26) are located cross-gradient from the plume and will be used to assure that the plume does not veer from its current trajectory. Upgradient and plume wells will be sampled and analyzed for the parameters listed in Table 10.1 to verify the effectiveness of the proposed remedial action.

10.4.2 Sentry Wells

Two sentry wells will be used to evaluate the migration of the leading edge of the dissolved contaminant plume. Both sentry wells (existing MW-42 and to-be-installed MW-43) are located directly in front of the leading edge of the contaminant plume. Both wells are within the predicted migration path of the dissolved contaminants. These wells will be used to verify the results of the Bioplume II model developed for this site. The conservative model predicts that contaminants should be first detected in these wells within 5 to 10 years. No BTEX or naphthalene concentration above 500 μg/L is expected in these wells at any time during the monitoring period. All of the sentry wells will be monitored for parameters listed in Table 10.2.

10.4.3 Point-of-Action Wells

Three POA groundwater monitoring wells will be located approximately 700 feet downgradient from the existing leading edge of the plume (i.e., downgradient from any detected concentrations of COPCs). The POA wells will be used to delineate the maximum downgradient extent of groundwater contamination. According to model predictions, site-related contaminants should never be measured at concentrations

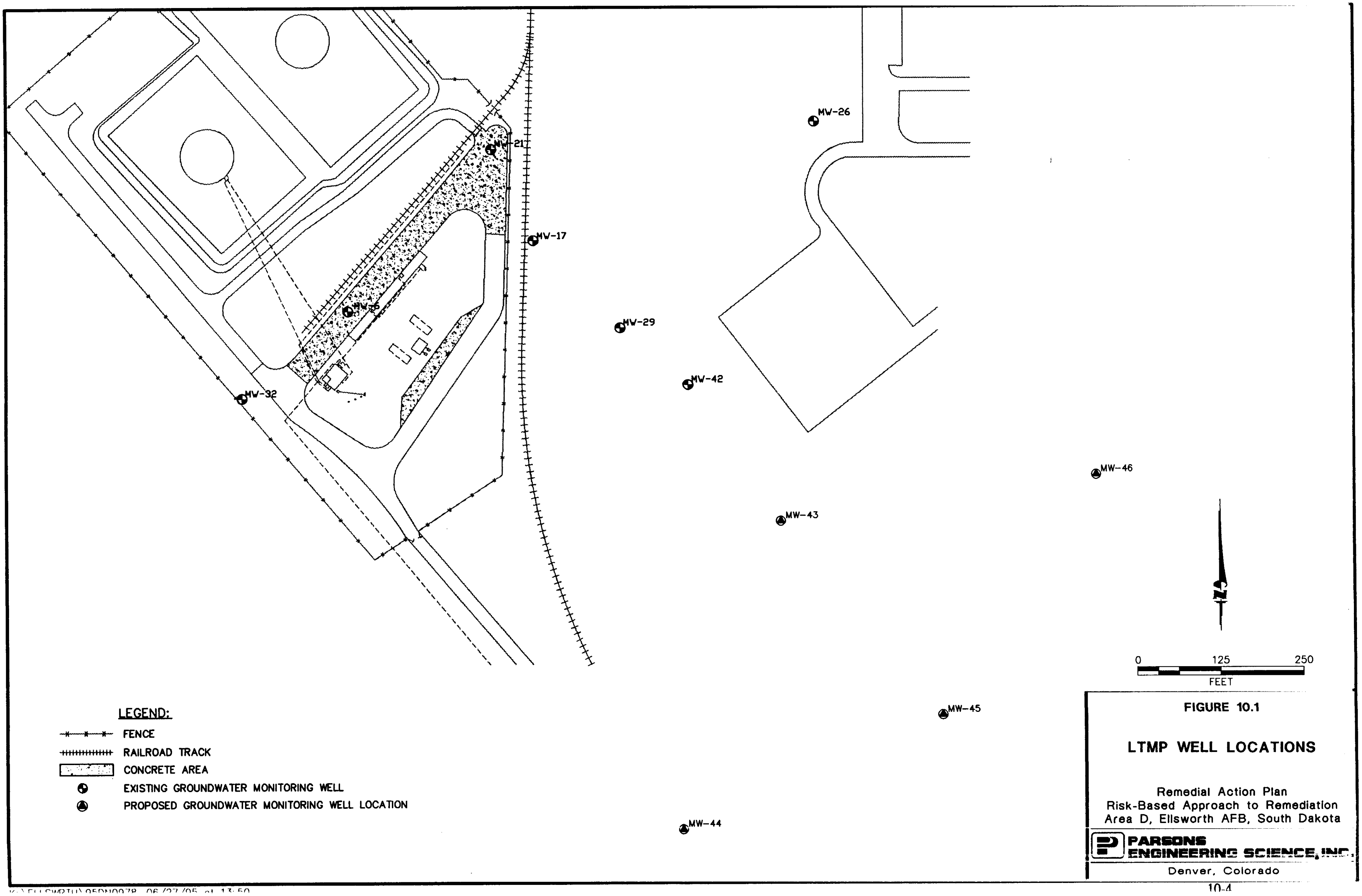


FIGURE 10.1

LTMP WELL LOCATIONS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

K:\ELLSWRTH\95DN0978 06/27/95 at 13:50

TABLE 10.1

GROUNDWATER MONITORING ANALYTICAL PROTOCOL FOR UPGRADIENT AND PLUME WELLS

REMEDIAL ACTION PLAN

RISK-BASED APPROACH TO REMEDIATION

AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Site -Specific Water MDL	Water Reporting Limit	Field or Fixed-Base Laboratory
Aromatic hydrocarbons (BTEX)	SW8020 (Gas Chromatography/ Mass Spectrometry method)	As described in latest version of *Test Methods for Evaluating Solid Waste* (EPA SW-846)	BTEX compounds (benzene, toluene, ethylbenzene, and total xylenes) have been identified as either groundwater COCs or compounds that can affect biodegradation of groundwater COCs	Annually	Collect water samples in a 40 milliliter volatile organic analysis vial with zero headspace; cool to 4°C; add hydrochloric acid to pH ≤ 2	See Table 2.1	See Table 2.1	Fixed-base
Polycylic aromatic hydrocarbons (PAHs)	SW8270 (Gas Chromatography/ Mass Spectrometry method)	As described in latest version *of Test Methods for Evaluating Solid Waste* (EPA SW-846)	PAH compound naphthalene has been identified as a groundwater COC	Annually	Collect water samples in a 1-liter glass container; cool to 4°C	See Table 2.1	See Table 2.1	Fixed-base
Redox potential	Direct-reading meter (Orion Model 290A with Orion Combination Redox 9678BN probe)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	The redox potential of ground water influences and is influenced by biologically mediated reactions: can be used as an indicator of the terminal electron acceptor process involved in COC biodegradation	Annually	Measure directly using a flow-through cell with probe portals. Probe should be standardized against Zobel solution	NA[a/]	0.0 pe units	Field
Dissolved oxygen	Direct-reading meter (YSI Model 50B with YSI 5739 probe)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	Reduced concentrations of dissolved oxygen indicate that microorganisms are facilitating oxygen reduction to biodegrade COCs	Annually	Measure directly using flow-through cell with probe portals. Probe should be calibrated with zero dissolved oxygen solution	NA	0.5 mg/L	Field

TABLE 10.1 (Continued)

GROUNDWATER MONITORING ANALYTICAL PROTOCOL FOR UPGRADIENT AND PLUME WELLS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Site Specific Water MDL	Water Reporting Limit	Field or Fixed-Base Laboratory
Nitrate (NO_3^{-1})	Colorimetric HACH 8039	Field only	Depleted nitrate concentrations indicate that microorganisms are facilitating nitrate reduction to biodegrade COCs	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis	0.01 mg/L	0.066 mg/L	Field
Nitrite (NO_2^{-1})	Colorimetric HACH 8040	Field only	Elevated concentrations of nitrite indicate that microorganisms are facilitating nitrate reduction to biodegrade COCs	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis	0.005 mg/L	0.01 mg/L	Field
Manganese (Mn^{+2})	Colorimetric HACH 8034	Field only	Elevated concentrations of reduced forms of manganese indicate that microorganisms are facilitating manganese reduction to biodegrade COCs	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis	0.01 mg/L	0.05 mg/L	Field
Ferrous iron (Fe^{2+})	Colorimetric HACH 8146	Field only	Elevated ferrous iron concentrations indicate that microorganisms are facilitating ferric iron reduction to biodegrade COCs	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis	0.01 mg/L	0.024 mg/L	Field
Total iron (Fe)	Colorimetric HACH 8008	Field only	Used to calculate the gross mass fraction of dissolved iron that has been reduced	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis	0.01 mg/L	0.024 mg/L	Field
Sulfate (SO_4^{2-})	Colorimetric HACH 8051	Field only	Reduced concentrations of sulfate indicate that microorganisms are facilitating sulfate reduction to biodegrade COCs	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis	0.01 mg/L	0.01 mg/L	Field
Sulfide (S^{-2})	Colorimetric HACH 8131	Field only	Elevated concentrations of sulfide forms indicate that microorganisms are facilitating sulfate reduction to biodegrade COCs	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis	NA	NA	Field

TABLE 10.1 (Continued)

GROUNDWATER MONITORING ANALYTICAL PROTOCOL FOR UPGRADIENT AND PLUME WELLS

REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Site-Specific Water MDL	Water Reporting Limit	Field or Fixed-Base Laboratory
Hydrogen sulfide (H_2S)	Colorimetric HACH 8131	Field only	Elevated concentrations of sulfide forms indicate that microorganisms are facilitating sulfate reduction to biodegrade COCs	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis	0.01 mg/L	0.024 mg/L	Field
pH	Direct-reading meter (Orion Model 140)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	Aerobic and anaerobic processes are pH-sensitive	Annually	Measure directly using a contained flow-through cell with probe portals. Probe should be calibrated using at least three pH standards	NA	0.00 pH units	Field
Temperature	Direct-reading meter	Field only	Metabolism rates for microorganisms depend on temperature	Annually	Measure directly using a contained flow-through cell with probe portals	NA	1.0 °C	Field
Conductivity	Direct-reading meter (Orion Model 140 with Conductivity Cell 014050)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	General water quality parameter used as a marker to verify that site samples are obtained from the same ground water system	Annually	Measure directly using a contained flow-through cell with probe portals. Probe is factory calibrated	NA	0.02 µmhos/cm	Field
Alkalinity (as $CaCO_3$)	Colorimetric HACH 8221	Field only	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system	Annually	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis.	NA	20.0 mg/L	Field

[a] NA = not applicable

TABLE 10.2

GROUNDWATER MONITORING ANALYTICAL PROTOCOL FOR POINT-OF-ACTION AND SENTRY WELLS

REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Site-Specific Water MDL	Water Reporting Limit	Field or Fixed-Base Laboratory
Aromatic hydrocarbons (BTEX)	SW8020 (Gas Chromatography/ Mass Spectrometry method SW8020	As described in latest version of *Test Methods for Evaluating Solid Waste* (EPA SW-846)	BTEX compounds have been identified as groundwater COCs or compounds of interest which may affect COC degradation	Annually	Collect water samples in a 40 mL VOA vial with zero headspace; cool to 4°C; add hydrochloric acid to pH ≤2	See Table 2.1	See Table 2.1	Fixed-base
Polycyclic aromatic hydrocarbons (PAHs)	SW8270 (Gas Chromatography/ Mass Spectrometry method)	As described in latest version *of Test Methods for Evaluating Solid Waste* (EPA SW-846)	PAH compound naphthalene has been identified as a groundwater COC	Annually	Collect water samples in a 1-liter glass container; cool to 4°C	See Table 2.1	See Table 2.1	Fixed-base
Redox potential	Direct-reading meter (Orion Model 290A with Orion Combination Redox 9678BN probe)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	The redox potential of ground water influences and is influenced by biologically mediated reactions: can be used as an indicator of the terminal electron acceptor process involved in COC biodegradation	Annually	Measure directly using a flow-through cell with probe portals. Probe should be standardized against Zobel solution	NA[a/]	0.0 pe units	Field
Dissolved oxygen	Direct-reading meter (YSI Model 50B with YSI 5739 probe)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	Reduced concentrations of dissolved oxygen indicate that microorganisms are facilitating oxygen reduction to biodegrade COCs	Annually	Measure directly using flow-through cell with probe portals. Probe should be calibrated with zero dissolved oxygen solution	NA	0.5 mg/L	Field

TABLE 10.2 (Continued)

GROUNDWATER MONITORING ANALYTICAL PROTOCOL FOR POINT-OF-ACTION AND SENTRY GROUNDWATER

REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Site-Specific Water MDL	Water Reporting Limit	Field or Fixed-Base Laboratory
pH	Direct-reading meter (Orion Model 140)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	Aerobic and anaerobic processes are pH-sensitive	Annually	Measure directly using a contained flow-through cell with probe portals. Probe should be calibrated using at least three pH standards	NA	0.00 pH units	Field
Temperature	Direct-reading meter	Field only	Metabolism rates for microorganisms depend on temperature	Annually	Measure directly using a contained flow-through cell with probe portals	NA	1.0 °C	Field
Conductivity	Direct-reading meter (Orion Model 140 with Conductivity Cell 014050)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	General water quality parameter used as a marker to verify that site samples are obtained from the same ground water system	Annually	Measure directly using a contained flow-through cell with probe portals. Probe is factory calibrated	NA	0.02 µmhos/cm	Field

[a] NA = not applicable

exceeding state groundwater standards in these wells. This monitoring will demonstrate plume containment and stability to facilitate the attainment of inactive-site status.

Three new wells (MW-44, MW-45, and MW-46) will be installed at POAs downgradient from the current contaminant plume. These wells also will be monitored to ensure that the contaminant plume is behaving according to conservative model predictions. The POA wells will be monitored for parameters listed in Table 10.2. The detection of site-related contaminants at levels exceeding state groundwater quality standards at any of the POA wells will trigger the need to evaluate possible contingency actions. The scope of contingency actions will be establish when concentrations of site-related contaminants exceeding groundwater standards appear in collected samples from any of the POA wells. These actions could include, but may not be limited to, the following:

- Additional investigation efforts to reevaluate results obtained during initial investigation activities;

- Reevaluation of model results to determine if concentrations of contaminants that may pose a risk to human health or the environment have the potential to migrate beyond Base boundaries (approximately 2 miles downgradient from the leading edge current plume); and

- Additional engineering evaluations to determine if more aggressive remedial efforts are necessary and/or feasible.

10.4.4 Point-of-Compliance Wells

Due to the 2-mile distance between the leading edge of the current plume and the Base boundary and the known existence of additional nonsite-related BTEX contamination between Area D and the downgradient Base boundary, no point-of-compliance wells, per the legal definition, have been identified or proposed for LTM at this time.

10.5 GROUNDWATER SAMPLING

This LTMP includes a comprehensive groundwater SAP. The LTMP, when implemented in accordance with the SAP, will verify that COC concentrations above promulgated state groundwater standards are not migrating downgradient of any of the POA wells. The SAP for all sampling related to this remedial action plan is provided in Appendix I. Sentry and POA wells will be sampled and analyzed periodically as described in Section 10.5.2 to verify that source removal technologies and natural processes are effectively reducing contaminant concentrations, mass, mobility, and toxicity. Reductions in COC toxicity will be implied by concentration and mass reduction (e.g., as COCs are biodegraded to less toxic compounds such as carbon dioxide and water).

10.5.1 Implementation Requirements

All LTM groundwater monitoring wells will be sampled and analyzed in accordance with Tables 10.1 and 10.2, respectively, to determine progress toward and compliance with the proposed chemical-specific cleanup criteria for Area D. All samples will be collected in accordance with the SAP. Additionally, QA/QC samples and procedures will be implemented as described in the SAP and the QAPP presented, respectively, in Appendices I and J.

10.5.2 Sampling Frequency

Each of the groundwater sampling points will be sampled annually for 5 years. After 5 years, the sampling frequency will be reevaluated based on previous sampling results and the Bioplume II model results presented in Section 6.6. If sampling results confirm the Bioplume II results, the sampling interval will be changed to every other year (biannually) to minimize monitoring costs. If the sampling results contradict the model predictions (i.e., the plume is migrating faster or at greater concentration than suggested by the conservative model), annual monitoring of all 11 wells in the LTM network will continue until the site is demonstrated to be eligible for inactive status classification or until contingency remedial actions are considered.

Based on the results of the Bioplume II model of the site, sampling will be required for a total of 22 years to attain inactive status. For cost estimation purposes, it is anticipated that the first 5 years will involve annual sampling, the next 15 years will involve biannual sampling, and the last 2 years will require semiannual sampling. Twenty-two years is the amount of time conservatively estimated to be required to achieve inactive status (i.e., to document plume stability) at Area D. A schedule of all sampling events prescribed by this LTMP is shown on Figure 9.1. If the data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, contingency remedial activities will be considered (Sections 9.3 and 10.2.3).

10.6 SOIL SAMPLING

Two years of bioventing is proposed as part of the recommended remedial alternative for soils at Area D. Sample data from vadose zone soils in the source area at Area D indicate that BTEX compounds are not present at concentrations that pose a risk to onsite workers or underlying groundwater quality (Sections 5 and 6). However, an engineered soil remedial technology (i.e., *in situ* bioventing) is proposed for Area D to satisfy the SDDENR (1994) requirement that all soils be remediated to the maximum extent practicable.

After 2 years of bioventing operation, 21 subsurface verification soil samples will be collected within the source area at Area D to assure that compound-specific contaminant concentrations and mass have been reduced to near or below analytical method PQLs. Three verification samples will be collected from the vicinity of each air injection well. Samples will be collected at 120-degree intervals around the well at a radius of approximately 15 feet. Samples will be collected using a Geoprobe®

hydraulic push sampler. Soil samples will be collected from the smear zone just above the groundwater surface. Previous investigations have shown this interval to be the area of greatest soil contamination at Area D. Additional sampling and analysis information is presented in Appendix I, the SAP.

10.6.1 Implementation Requirements

All soil samples will be collected in accordance with the site-specific SAP presented in Appendix I and analyzed as specified in Table 10.3. QA/QC procedures will be applied as described in the SAP and QAPP (Appendices I and J, respectively).

10.6.2 Sampling Frequency

Soil samples will be collected after 2 years of bioventing operation. This is the amount of time conservatively estimated to be required to remove BTEX compounds from unsaturated soils at Area D. Sampling activities are shown on the LTMP schedule presented in Figure 9.1. If the data collected at this time indicate the need for additional remedial activities at the site, system operation will continue and soil sampling will be conducted annually until contaminants have been remediated to the maximum extent practicable.

10.7 LAND USE CONTROLS VERIFICATION

Long-term site management responsibilities will include verification that any future land uses are consistent with an inactive status designation. The monitoring program specified herein is designed to document plume stability and eventual contaminant mass removal. These data will be used to confirm that there is no need for additional exposure controls at or downgradient from Area D to minimize potential human health risks and unacceptable environmental impacts. Any changes in activities conducted in areas impacted by Area D contamination will be documented.

Any future uses of the site should preclude use of impacted groundwater as a source of potable water until such time that state groundwater standards have been attained at every monitoring point. In addition to future site use reviews, interim confirmation of land and groundwater use controls are proposed to include documenting the land zoning, types of potential onsite receptors, and the kinds of activities in which these potential receptors may engage at the site. For example, this RAP recommends that extensive soil excavation in Area D should be minimized to the extent practicable to prevent worker contact with contaminated soil and groundwater. This administrative confirmation step will be formally documented when the results of site analytical sampling events are prepared for review and assessment. Any significant changes in land use will be identified, and any modification of the recommended remedial alternative that may be required to protect human health and the environment will be identified and proposed for review and implementation, as necessary.

TABLE 10.3

VERIFICATION SOIL SAMPLING ANALYTICAL PROTOCOL
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Site-Specific MDL	Reporting Limit	Field or Fixed-Base Laboratory
Aromatic hydrocarbons (BTEX)	SW8020 (Gas Chromatography/ Mass Spectrometry Method)	As described in latest version of *Test Methods for Evaluating Solid Waste* (EPA SW-846)	BTEX compounds have been identified as soil contaminants	After 2 years of bioventing	Collect 4 grams of soil in a glass container with a Teflon®-lined lid; Cool to 4°C	See Table 2.1	See Table 2.1	Fixed-base
Total petroleum hydrocarbons (TPH); volatile and extractable	SW8015 (Gas Chromatography/ Mass Spectrometry Method)	As described in latest version of *Test Methods for Evaluating Solid Waste* (EPA SW-846); reference is the California LUFT manual	Gross indicator of extent of residual soil contamination	After 2 years of bioventing	Collect 100g of soil in a glass container with a Teflon-lined lid; Cool to 4°C.	See Table 2.1	See Table 2.1	Fixed-base

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APPENDIX A

ANALYTICAL DATA FOR 1994 SAMPLING EVENT

TABLE A.1
SOIL DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
SC-1-1	28-Sep-94			110	mg/kg	M8015
			Total Volatile Hydrocarbons	4.2	mg/kg	M8015
			Benzene	1.1 J [b/]	µg/kg	SW8020
			Toluene	65	µg/kg	SW8020
			Ethylbenzene	12	µg/kg	SW8020
			Xylenes (Total)	61	µg/kg	SW8020
			1,3,5-Trimethylbenzene	54	µg/kg	SW8020
			1,2,4-Trimethylbenzene	110	µg/kg	SW8020
			1,2,3-Trimethylbenzene	60	µg/kg	SW8020
SC-1-2	28-Sep-94		Total Extractable Hydrocarbons	96	mg/kg	M8015
			Total Volatile Hydrocarbons	6.5	mg/kg	M8015
			Benzene	1.2 J	µg/kg	SW8020
			Toluene	39	µg/kg	SW8020
			Ethylbenzene	82	µg/kg	SW8020
			Xylenes (Total)	1500	µg/kg	SW8020
			1,3,5-Trimethylbenzene	570	µg/kg	SW8020
			1,2,4-Trimethylbenzene	1200	µg/kg	SW8020
			1,2,3-Trimethylbenzene	740	µg/kg	SW8020
SC-2-1	28-Sep-94		Total Extractable Hydrocarbons	11 U [c/]	mg/kg	M8015
			Total Volatile Hydrocarbons	0.11 U	mg/kg	M8015
			Benzene	0.44 U	µg/kg	SW8020
			Toluene	4.4 U	µg/kg	SW8020
			Ethylbenzene	4.4 U	µg/kg	SW8020
			Xylenes (Total)	4.4 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	0.7 J	µg/kg	SW8020
			1,2,4-Trimethylbenzene	1.1 J	µg/kg	SW8020
			1,2,3-Trimethylbenzene	0.5 J	µg/kg	SW8020
SC-2-2	28-Sep-94		Total Extractable Hydrocarbons	11 U	mg/kg	M8015
			Total Volatile Hydrocarbons	0.11 U	mg/kg	M8015
			Benzene	0.8 J	µg/kg	SW8020
			Toluene	14	µg/kg	SW8020
			Ethylbenzene	0.8 J	µg/kg	SW8020
			Xylenes (Total)	4.4 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	1.9 J	µg/kg	SW8020
			1,2,4-Trimethylbenzene	3.2 J	µg/kg	SW8020
			1,2,3-Trimethylbenzene	1.2 J	µg/kg	SW8020
MW-25	12-Sep-94	14.50 - 15.50	Benzene	0.49 U	µg/kg	SW8020
			Toluene	4.9 U	µg/kg	SW8020
			Ethylbenzene	4.9 U	µg/kg	SW8020
			Xylenes (Total)	4.9 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	4.9 U	µg/kg	SW8020

TABLE A.1
SOIL DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			1,2,4-Trimethylbenzene	4.9 U	µg/kg	SW8020
			1,2,3-Trimethylbenzene	4.9 U	µg/kg	SW8020
MW-26	13-Sep-94	23.50 - 24.50	Total Extractable Hydrocarbons	12 U	mg/kg	M8015
			Total Volatile Hydrocarbons	1.2 J	mg/kg	M8015
			Benzene	0.5 U	µg/kg	SW8020
			Toluene	5 U	µg/kg	SW8020
			Ethylbenzene	5 U	µg/kg	SW8020
			Xylenes (Total)	5 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	5 U	µg/kg	SW8020
			1,2,4-Trimethylbenzene	5 U	µg/kg	SW8020
			1,2,3-Trimethylbenzene	5 U	µg/kg	SW8020
MW-27	14-Sep-94	23.50 - 24.50	Benzene	0.47 U	µg/kg	SW8020
			Toluene	4.7 U	µg/kg	SW8020
			Ethylbenzene	4.7 U	µg/kg	SW8020
			Xylenes (Total)	4.7 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	4.7 U	µg/kg	SW8020
			1,2,4-Trimethylbenzene	4.7 U	µg/kg	SW8020
			1,2,3-Trimethylbenzene	4.7 U	µg/kg	SW8020
MW-28	14-Sep-94	18.50 - 19.50	Benzene	0.44 U	µg/kg	SW8020
			Toluene	4.4 U	µg/kg	SW8020
			Ethylbenzene	4.4 U	µg/kg	SW8020
			Xylenes (Total)	4.4 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	4.4 U	µg/kg	SW8020
			1,2,4-Trimethylbenzene	4.4 U	µg/kg	SW8020
			1,2,3-Trimethylbenzene	4.4 U	µg/kg	SW8020
MW-29	15-Sep-94	16.50 - 17.50	Total Extractable Hydrocarbons	59	mg/kg	M8015
			Total Volatile Hydrocarbons	17	mg/kg	M8015
			Benzene	0.43 U	µg/kg	SW8020
			Toluene	1.1 J	µg/kg	SW8020
			Ethylbenzene	1.5 J	µg/kg	SW8020
			Xylenes (Total)	6	µg/kg	SW8020
			1,3,5-Trimethylbenzene	4.8	µg/kg	SW8020
			1,2,4-Trimethylbenzene	8.6	µg/kg	SW8020
			1,2,3-Trimethylbenzene	1.4 J	µg/kg	SW8020
MW-30	15-Sep-94	19.50 - 20.50	Benzene	1.2 J	µg/kg	SW8020
			Toluene	1.1 J	µg/kg	SW8020
			Ethylbenzene	1.1 J	µg/kg	SW8020
			Xylenes (Total)	4.1 J	µg/kg	SW8020
			1,3,5-Trimethylbenzene	2.9 J	µg/kg	SW8020
			1,2,4-Trimethylbenzene	4.6	µg/kg	SW8020
			1,2,3-Trimethylbenzene	0.9 J	µg/kg	SW8020

TABLE A.1
SOIL DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-31	16-Sep-94	20.50 - 21.50	Total Extractable Hydrocarbons	12 U	mg/kg	M8015
			Total Volatile Hydrocarbons	4.9	mg/kg	M8015
			Benzene	4.4 J	µg/kg	SW8020
			Toluene	4.4 J	µg/kg	SW8020
			Ethylbenzene	33	µg/kg	SW8020
			Xylenes (Total)	150	µg/kg	SW8020
			1,3,5-Trimethylbenzene	43	µg/kg	SW8020
			1,2,4-Trimethylbenzene	120	µg/kg	SW8020
			1,2,3-Trimethylbenzene	44	µg/kg	SW8020
MW-32	19-Sep-94	17.50 - 18.50	Benzene	0.46 U	µg/kg	SW8020
			Toluene	4.6 U	µg/kg	SW8020
			Ethylbenzene	4.6 U	µg/kg	SW8020
			Xylenes (Total)	4.6 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	4.6 U	µg/kg	SW8020
			1,2,4-Trimethylbenzene	4.6 U	µg/kg	SW8020
			1,2,3-Trimethylbenzene	4.6 U	µg/kg	SW8020
MW-33	19-Sep-94	22.50 - 23.50	Benzene	0.46 U	µg/kg	SW8020
			Toluene	4.6 U	µg/kg	SW8020
			Ethylbenzene	4.6 U	µg/kg	SW8020
			Xylenes (Total)	4.6 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	4.6 U	µg/kg	SW8020
			1,2,4-Trimethylbenzene	4.6 U	µg/kg	SW8020
			1,2,3-Trimethylbenzene	4.6 U	µg/kg	SW8020
MW-34	20-Sep-94	24.50 - 25.50	Benzene	13 J	µg/kg	SW8020
			Toluene	45	µg/kg	SW8020
			Ethylbenzene	260	µg/kg	SW8020
			Xylenes (Total)	880	µg/kg	SW8020
			1,3,5-Trimethylbenzene	430	µg/kg	SW8020
			1,2,4-Trimethylbenzene	1100	µg/kg	SW8020
			1,2,3-Trimethylbenzene	540	µg/kg	SW8020
MW-35	20-Sep-94	21.50 - 22.50	Total Extractable Hydrocarbons	11 U	mg/kg	M8015
			Total Volatile Hydrocarbons	0.4 J	mg/kg	M8015
			Benzene	0.43 U	µg/kg	SW8020
			Toluene	0.4 J	µg/kg	SW8020
			Ethylbenzene	4.3 U	µg/kg	SW8020
			Xylenes (Total)	4.3 U	µg/kg	SW8020
			1,3,5-Trimethylbenzene	0.4 J	µg/kg	SW8020
			1,2,4-Trimethylbenzene	0.5 J	µg/kg	SW8020
			1,2,3-Trimethylbenzene	4.3 U	µg/kg	SW8020
MW-36	21-Sep-94	21.50 - 22.50	Total Extractable Hydrocarbons	12 U	mg/kg	M8015
			Total Volatile Hydrocarbons	1.7 J	mg/kg	M8015

TABLE A.1
SOIL DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Benzene	0.48 U	µg/kg	SW8020
			Toluene	4.8 U	µg/kg	SW8020
			Ethylbenzene	0.8 J	µg/kg	SW8020
			Xylenes (Total)	2.3 J	µg/kg	SW8020
			1,3,5-Trimethylbenzene	2.9 J	µg/kg	SW8020
			1,2,4-Trimethylbenzene	1.9 J	µg/kg	SW8020
			1,2,3-Trimethylbenzene	0.8 J	µg/kg	SW8020
MW-37	21-Sep-94	21.50 - 22.50	Benzene	8 J	µg/kg	SW8020
			Toluene	66	µg/kg	SW8020
			Ethylbenzene	110	µg/kg	SW8020
			Xylenes (Total)	460	µg/kg	SW8020
			1,3,5-Trimethylbenzene	380	µg/kg	SW8020
			1,2,4-Trimethylbenzene	1100	µg/kg	SW8020
			1,2,3-Trimethylbenzene	570	µg/kg	SW8020
MW-39	22-Sep-94	18.50 - 19.50	Total Extractable Hydrocarbons	210	mg/kg	M8015
			Total Volatile Hydrocarbons	14	mg/kg	M8015
			Benzene	2.3 U	µg/kg	SW8020
			Toluene	20 J	µg/kg	SW8020
			Ethylbenzene	220	µg/kg	SW8020
			Xylenes (Total)	1100	µg/kg	SW8020
			1,3,5-Trimethylbenzene	1900	µg/kg	SW8020
			1,2,4-Trimethylbenzene	3500	µg/kg	SW8020
			1,2,3-Trimethylbenzene	2200	µg/kg	SW8020
MW-40	23-Sep-94	13.50 - 14.50	Total Extractable Hydrocarbons	3700	mg/kg	M8015
			Total Volatile Hydrocarbons	1900	mg/kg	M8015
			Benzene	640	µg/kg	SW8020
			Toluene	3700	µg/kg	SW8020
			Ethylbenzene	12000	µg/kg	SW8020
			Xylenes (Total)	74000	µg/kg	SW8020
			1,3,5-Trimethylbenzene	38000	µg/kg	SW8020
			1,2,4-Trimethylbenzene	76000	µg/kg	SW8020
			1,2,3-Trimethylbenzene	6300	µg/kg	SW8020
SB-1	27-Aug-94	16.50 - 17.50	Benzene	0.53 U	µg/kg	SW8020
			Toluene	6.9	µg/kg	SW8020
			Ethylbenzene	1.1 J	µg/kg	SW8020
			Xylenes (Total)	4.8 J	µg/kg	SW8020
			1,3,5-Trimethylbenzene	0.5 J	µg/kg	SW8020
			1,2,4-Trimethylbenzene	2.9 J	µg/kg	SW8020
			1,2,3-Trimethylbenzene	0.9 J	µg/kg	SW8020
MW-40	27-Aug-94	9.00 - 10.00	Benzene	1100	µg/kg	SW8020
			Toluene	4100	µg/kg	SW8020

TABLE A.1
SOIL DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Ethylbenzene	9800	µg/kg	SW8020
			Xylenes (Total)	57000	µg/kg	SW8020
			1,3,5-Trimethylbenzene	24000	µg/kg	SW8020
			1,2,4-Trimethylbenzene	63000	µg/kg	SW8020
			1,2,3-Trimethylbenzene	20000	µg/kg	SW8020
MW-36	28-Aug-94	22.50 - 23.50	Total Extractable Hydrocarbons	200	mg/kg	M8015
			Benzene	16 U	µg/kg	SW8020
			Toluene	470	µg/kg	SW8020
			Ethylbenzene	2300	µg/kg	SW8020
			Xylenes (Total)	9700	µg/kg	SW8020
			1,3,5-Trimethylbenzene	6400	µg/kg	SW8020
			1,2,4-Trimethylbenzene	12000	µg/kg	SW8020
			1,2,3-Trimethylbenzene	5800	µg/kg	SW8020

[a/] Sample Interval in feet below ground surface

[b/] J = Estimated Concentration of Analyte

[c/] U = Analyte Not Detected Above Method Detection Limit

TABLE A.2
SOIL DATA FOR OTHER ANALYSIS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-26	13-Sep-94	23.50 - 24.50	Total Organic Carbon	0.42 J [b]	%	SW9060
MW-31	16-Sep-94	20.50 - 21.50	Total Organic Carbon	0.51	%	SW9060
MW-34	20-Sep-94	25.50 - 26.50	Total Organic Carbon	1.1	%	SW9060
MW-39	22-Sep-94	14.50 - 15.50	Moisture, Percent	25.2	%	D2216
			Gravel	0	%	D422
			Sand	13.54	%	D422
			Silt	86.46	%	D422
MW-39	22-Sep-94	18.50 - 19.50	Moisture, Percent	13.2	%	D2216
			Gravel	58.99	%	D422
			Sand	27.12	%	D422
			Silt	13.88	%	D422
			Total Organic Carbon	0.65	%	SW9060
MW-40	23-Sep-94	13.50 - 14.50	Moisture, Percent	17.5	%	D2216
			Gravel	0.71	%	D422
			Sand	16.28	%	D422
			Silt	83.01	%	D422
MW-40	23-Sep-94	17.50 - 18.50	Moisture, Percent	9.2	%	D2216
			Gravel	73.4	%	D422
			Sand	20.06	%	D422
			Silt	6.54	%	D422
MW-26	13-Sep-94	23.50 - 24.50	pH	8.84	pH units	SW9045
MW-31	16-Sep-94	20.50 - 21.50	pH	9.63	pH units	SW9045
MW-34	20-Sep-94	25.50 - 26.50	pH	9.67	pH units	SW9045
MW-39	22-Sep-94	18.50 - 19.50	pH	9.94	pH units	SW9045

[a] Sample Interval in feet below ground surface

[b] J = Estimated Concentration of Analyte

TABLE A.3
SOIL GAS DATA
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
SG1	27-Aug-94	3.50 -4.00	Benzene	24	µg/L	TO3
			Toluene	0.22 U [b/]	µg/L	TO3
			Ethylbenzene	22	µg/L	TO3
			Xylenes (Total)	29	µg/L	TO3
			Petroleum Hydrocarbons	26000	µg/L	TO3
SG10	27-Aug-94	3.00 -3.50	Benzene	0.007 U	µg/L	TO3
			Toluene	0.009 U	µg/L	TO3
			Ethylbenzene	0.01 U	µg/L	TO3
			Xylenes (Total)	0.049	µg/L	TO3
			Petroleum Hydrocarbons	1.4	µg/L	TO3
SG4	27-Aug-94	3.00 -3.50	Benzene	0.19 U	µg/L	TO3
			Toluene	0.22 U	µg/L	TO3
			Ethylbenzene	3.3	µg/L	TO3
			Xylenes (Total)	4.4	µg/L	TO3
			Petroleum Hydrocarbons	3100	µg/L	TO3
SG6	27-Aug-94	3.00 -3.50	Benzene	0.007 U	µg/L	TO3
			Toluene	0.11	µg/L	TO3
			Ethylbenzene	0.01 U	µg/L	TO3
			Xylenes (Total)	0.12	µg/L	TO3
			Petroleum Hydrocarbons	16	µg/L	TO3

[a/] Sample Interval in feet below ground surface

[b/] U = Analyte Not Detected Above Method Detection Limit

TABLE A.4
SOIL FLUX DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a] (begining-ending)	Analyte	Result	Units	Analytical Method
FLUX1	26-Aug-94	0.00 -0.00	Benzene	0.007 U [b]	µg/L	TO3
			Toluene	0.073	µg/L	TO3
			Ethylbenzene	0.062	µg/L	TO3
			Xylenes (Total)	0.34	µg/L	TO3
			Petroleum Hydrocarbons	9.7	µg/L	TO3
FLUX2	26-Aug-94	0.00 -0.00	Benzene	0.007 U	µg/L	TO3
			Toluene	0.073	µg/L	TO3
			Ethylbenzene	0.013	µg/L	TO3
			Xylenes (Total)	0.097	µg/L	TO3
			Petroleum Hydrocarbons	1.9	µg/L	TO3
FLUX3	26-Aug-94	0.00 -0.00	Benzene	0.007 U	µg/L	TO3
			Toluene	0.046	µg/L	TO3
			Ethylbenzene	0.01 U	µg/L	TO3
			Xylenes (Total)	0.04	µg/L	TO3
			Petroleum Hydrocarbons	0.65	µg/L	TO3
FLUX4	26-Aug-94	0.00 -0.00	Benzene	0.007 U	µg/L	TO3
			Toluene	0.034	µg/L	TO3
			Ethylbenzene	0.01 U	µg/L	TO3
			Xylenes (Total)	0.009	µg/L	TO3
			Petroleum Hydrocarbons	0.78	µg/L	TO3

[a] Sample Interval in feet below ground surface

[b] U = Analyte Not Detected Above Method Detection Limit

TABLE A.5
GROUNDWATER DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-13	25-Aug-94	0.00 -0.00	Benzene	0.4 U [b/]	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-15	25-Aug-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-16	25-Aug-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-23	25-Aug-94	0.00 -0.00	Total Extractable Hydrocarbons	0.5 U	mg/L	M8015
			Total Volatile Hydrocarbons	0.1 U	mg/L	M8015
			Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-25	30-Sep-94	0.00 -0.00	Total Extractable Hydrocarbons	0.5 U	mg/L	M8015
			Total Volatile Hydrocarbons	0.1 U	mg/L	M8015
			Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	0.6 J [c/]	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-26	30-Sep-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020

TABLE A.5
GROUNDWATER DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
			Trichloroethene	5 U	µg/L	SW8260
MW-27	4-Oct-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
			Trichloroethene	5 U	µg/L	SW8260
MW-28	1-Oct-94	0.00 -0.00	Benzene	1.9 J	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	1.5 J	µg/L	SW8020
			Xylenes (Total)	2.1 J	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	2.7 J	µg/L	SW8020
			1,2,3-Trimethylbenzene	0.7 J	µg/L	SW8020
MW-29	2-Oct-94	0.00 -0.00	Total Extractable Hydrocarbons	1.8	mg/L	M8015
			Total Volatile Hydrocarbons	1.9	mg/L	M8015
			Benzene	260	µg/L	SW8020
			Toluene	1.2 J	µg/L	SW8020
			Ethylbenzene	87	µg/L	SW8020
			Xylenes (Total)	240	µg/L	SW8020
			1,3,5-Trimethylbenzene	25	µg/L	SW8020
			1,2,4-Trimethylbenzene	110	µg/L	SW8020
			1,2,3-Trimethylbenzene	39	µg/L	SW8020
MW-30	1-Oct-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-31	2-Oct-94	0.00 -0.00	Benzene	1500	µg/L	SW8020
			Toluene	8.3	µg/L	SW8020
			Ethylbenzene	470	µg/L	SW8020
			Xylenes (Total)	1700	µg/L	SW8020

TABLE A.5
GROUNDWATER DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			1,3,5-Trimethylbenzene	90	µg/L	SW8020
			1,2,4-Trimethylbenzene	420	µg/L	SW8020
			1,2,3-Trimethylbenzene	120	µg/L	SW8020
MW-32	4-Oct-94	0.00 -0.00	Total Extractable Hydrocarbons	0.5 U	mg/L	M8015
			Total Volatile Hydrocarbons	0.3	mg/L	M8015
			Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-32	9-Nov-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-33	2-Oct-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-34	3-Oct-94	0.00 -0.00	Total Extractable Hydrocarbons	7	mg/L	M8015
			Total Volatile Hydrocarbons	2.6	mg/L	M8015
			Benzene	220	µg/L	SW8020
			Toluene	8.8	µg/L	SW8020
			Ethylbenzene	210	µg/L	SW8020
			Xylenes (Total)	570	µg/L	SW8020
			1,3,5-Trimethylbenzene	140	µg/L	SW8020
			1,2,4-Trimethylbenzene	390	µg/L	SW8020
			1,2,3-Trimethylbenzene	180	µg/L	SW8020
MW-35	3-Oct-94	0.00 -0.00	Total Extractable Hydrocarbons	5.2	mg/L	M8015
			Total Volatile Hydrocarbons	3.9	mg/L	M8015
			Benzene	200	µg/L	SW8020
			Toluene	2.8 J	µg/L	SW8020
			Ethylbenzene	220	µg/L	SW8020
			Xylenes (Total)	550	µg/L	SW8020

TABLE A.5
GROUNDWATER DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			1,3,5-Trimethylbenzene	160	µg/L	SW8020
			1,2,4-Trimethylbenzene	470	µg/L	SW8020
			1,2,3-Trimethylbenzene	130	µg/L	SW8020
MW-39	5-Oct-94	0.00 -0.00	Total Extractable Hydrocarbons	24	mg/L	M8015
			Total Volatile Hydrocarbons	12	mg/L	M8015
			Benzene	3400	µg/L	SW8020
			Toluene	19	µg/L	SW8020
			Ethylbenzene	390	µg/L	SW8020
			Xylenes (Total)	790	µg/L	SW8020
			1,3,5-Trimethylbenzene	120	µg/L	SW8020
			1,2,4-Trimethylbenzene	450	µg/L	SW8020
			1,2,3-Trimethylbenzene	220	µg/L	SW8020
MW-40	5-Oct-94	0.00 -0.00	Total Extractable Hydrocarbons	8.5	mg/L	M8015
			Total Volatile Hydrocarbons	19	mg/L	M8015
			Benzene	2100	µg/L	SW8020
			Toluene	29	µg/L	SW8020
			Ethylbenzene	400	µg/L	SW8020
			Xylenes (Total)	1800	µg/L	SW8020
			1,3,5-Trimethylbenzene	92	µg/L	SW8020
			1,2,4-Trimethylbenzene	650	µg/L	SW8020
			1,2,3-Trimethylbenzene	240	µg/L	SW8020
MW-41	9-Nov-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-42	9-Nov-94	0.00 -0.00	Benzene	0.4 U	µg/L	SW8020
			Toluene	4 U	µg/L	SW8020
			Ethylbenzene	4 U	µg/L	SW8020
			Xylenes (Total)	4 U	µg/L	SW8020
			1,3,5-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,4-Trimethylbenzene	4 U	µg/L	SW8020
			1,2,3-Trimethylbenzene	4 U	µg/L	SW8020
MW-6	25-Aug-94	0.00 -0.00	Benzene	2000	µg/L	SW8020
			Toluene	35 J	µg/L	SW8020
			Ethylbenzene	640	µg/L	SW8020
			Xylenes (Total)	2700	µg/L	SW8020
			1,3,5-Trimethylbenzene	850	µg/L	SW8020
			1,2,4-Trimethylbenzene	2800	µg/L	SW8020

TABLE A.5
GROUNDWATER DATA FOR VOLATILE ORGANIC COMPOUNDS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a] (begining-ending)	Analyte	Result	Units	Analytical Method
			1,2,3-Trimethylbenzene	1200	µg/L	SW8020

[a] Sample Interval in feet below ground surface

[b] U = Analyte Not Detected Above Method Detection Limit

[c] J = Estimated Concentration of Analyte

TABLE A.6
GROUNDWATER DATA FOR SEMIVOLATILE ORGANIC COMPOUND
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-16	25-Aug-94	0.00 -0.00	Naphthalene	10 U [b/]	μg/L	SW8270
MW-29	2-Oct-94	0.00 -0.00	Naphthalene	28	μg/L	SW8270
MW-31	2-Oct-94	0.00 -0.00	Naphthalene	180	μg/L	SW8270
MW-35	3-Oct-94	0.00 -0.00	Naphthalene	160	μg/L	SW8270
MW-39	5-Oct-94	0.00 -0.00	Naphthalene	300	μg/L	SW8270
MW-40	5-Oct-94	0.00 -0.00	Naphthalene	230	μg/L	SW8270

[a/] Sample Interval in feet below ground surface

[b/] U = Analyte Not Detected Above Method Detection Limit

TABLE A.7
GROUNDWATER DATA FOR OTHER RELAVENT ANALYSES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-1	24-Aug-94	0.00 -0.00	Dissolved Oxygen	4.5 J [b/]	mg/L	FDO
			Iron, Total	0.02 J	mg/L	H8008
			Nitrate	0.9 J	mg/L	H8039
			Sulfate	887 J	mg/L	H8051
			Hydrogen Sulfide	0.024 UJ	mg/L	H8131
			Iron, Ferrous	0.02 J	mg/L	H8146
			Carbon Dioxide	48 J	mg/L	H8223
			Nitrite	0.003 J	mg/L	H8507
MW-13	25-Aug-94	0.00 -0.00	Dissolved Oxygen	6.4 J	mg/L	FDO
			Iron, Total	0.32 J	mg/L	H8008
			Nitrate	0.066 UJ	mg/L	H8039
			Sulfate	76.51 J	mg/L	H8051
			Iron, Ferrous	0.04 J	mg/L	H8146
			Carbon Dioxide	20 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-14	25-Aug-94	0.00 -0.00	Dissolved Oxygen	5.9 J	mg/L	FDO
			Iron, Total	0.08 J	mg/L	H8008
			Nitrate	0.066 UJ	mg/L	H8039
			Sulfate	3600 J	mg/L	H8051
			Iron, Ferrous	0.07 J	mg/L	H8146
			Carbon Dioxide	60 J	mg/L	H8223
			Nitrite	0.002 J	mg/L	H8507
MW-15	25-Aug-94	0.00 -0.00	Dissolved Oxygen	1.5 J	mg/L	FDO
			Iron, Total	0.87 J	mg/L	H8008
			Nitrate	0.066 UJ	mg/L	H8039
			Sulfate	592 J	mg/L	H8051
			Iron, Ferrous	0.55 J	mg/L	H8146
			Carbon Dioxide	70 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-16	25-Aug-94	0.00 -0.00	Carbon Dioxide	488	mg/L	COU-02
			Dissolved Oxygen	2.8 J	mg/L	FDO
			Iron, Total	0.09 J	mg/L	H8008
			Nitrate	0.6 J	mg/L	H8039
			Sulfate	60.38 J	mg/L	H8051
			Hydrogen Sulfide	0.024 UJ	mg/L	H8131
			Iron, Ferrous	0.08 J	mg/L	H8146
			Carbon Dioxide	40 J	mg/L	H8223
			Nitrite	0.006 J	mg/L	H8507
			Methane	0.001 U [c/]	mg/L	RSK175
MW-17	26-Aug-94	0.00 -0.00	Dissolved Oxygen	0.5 J	mg/L	FDO
			Iron, Total	2.22 J	mg/L	H8008

TABLE A.7
GROUNDWATER DATA FOR OTHER RELAVENT ANALYSES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Nitrate	1.6 J	mg/L	H8039
			Sulfate	0.01 UJ	mg/L	H8051
			Hydrogen Sulfide	0.024 UJ	mg/L	H8131
			Iron, Ferrous	0.65 J	mg/L	H8146
			Carbon Dioxide	40 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-18	26-Aug-94	0.00 -0.00	Dissolved Oxygen	5.4 J	mg/L	FDO
			Iron, Total	0.25 J	mg/L	H8008
			Nitrate	0.066 UJ	mg/L	H8039
			Sulfate	1810 J	mg/L	H8051
			Iron, Ferrous	0.15 J	mg/L	H8146
			Carbon Dioxide	40 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-19	26-Aug-94	0.00 -0.00	Dissolved Oxygen	6.2 J	mg/L	FDO
			Iron, Total	0.17 J	mg/L	H8008
			Nitrate	0.7 J	mg/L	H8039
			Sulfate	1580 J	mg/L	H8051
			Hydrogen Sulfide	0.024 UJ	mg/L	H8131
			Iron, Ferrous	0.11 J	mg/L	H8146
			Carbon Dioxide	100 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-2	24-Aug-94	0.00 -0.00	Dissolved Oxygen	0.2 J	mg/L	FDO
			Iron, Total	4.42 J	mg/L	H8008
			Nitrate	0.066 UJ	mg/L	H8039
			Sulfate	12.01 J	mg/L	H8051
			Hydrogen Sulfide	0.05 J	mg/L	H8131
			Iron, Ferrous	3.45 J	mg/L	H8146
			Carbon Dioxide	110 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-20	26-Aug-94	0.00 -0.00	Dissolved Oxygen	3.5 J	mg/L	FDO
			Iron, Total	1.79 J	mg/L	H8008
			Nitrate	1.9 J	mg/L	H8039
			Sulfate	2770 J	mg/L	H8051
			Hydrogen Sulfide	1 J	mg/L	H8131
			Iron, Ferrous	1.8 J	mg/L	H8146
			Carbon Dioxide	50 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-21	26-Aug-94	0.00 -0.00	Dissolved Oxygen	6.2 J	mg/L	FDO
			Iron, Total	0.18 J	mg/L	H8008
			Nitrate	0.3 J	mg/L	H8039
			Sulfate	373 J	mg/L	H8051

TABLE A.7
GROUNDWATER DATA FOR OTHER RELAVENT ANALYSES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Hydrogen Sulfide	0.024 UJ	mg/L	H8131
			Iron, Ferrous	0.1 J	mg/L	H8146
			Carbon Dioxide	35 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-22	26-Aug-94	0.00 -0.00	Dissolved Oxygen	2.5 J	mg/L	FDO
			Iron, Total	1.48 J	mg/L	H8008
			Nitrate	0.066 UJ	mg/L	H8039
			Sulfate	3088 J	mg/L	H8051
			Hydrogen Sulfide	0.8 J	mg/L	H8131
			Iron, Ferrous	1.52 J	mg/L	H8146
			Carbon Dioxide	50 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-23	25-Aug-94	0.00 -0.00	Dissolved Oxygen	5.5 J	mg/L	FDO
			Iron, Total	0.27 J	mg/L	H8008
			Nitrate	0.066 UJ	mg/L	H8039
			Sulfate	894.3 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.34 J	mg/L	H8146
			Carbon Dioxide	35 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-24	26-Aug-94	0.00 -0.00	Dissolved Oxygen	3.6 J	mg/L	FDO
			Iron, Total	0.04 J	mg/L	H8008
			Nitrate	3.3 J	mg/L	H8039
			Sulfate	250.7 J	mg/L	H8051
			Hydrogen Sulfide	0.05 J	mg/L	H8131
			Iron, Ferrous	0.024 UJ	mg/L	H8146
			Carbon Dioxide	35 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-25	30-Sep-94	0.00 -0.00	Carbon Dioxide	554	mg/L	COU-02
			Dissolved Oxygen	0.33 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.9 J	mg/L	H8008
			Nitrate	1.6 J	mg/L	H8039
			Sulfate	1.77 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.06 J	mg/L	H8146
			Carbon Dioxide	40 J	mg/L	H8223
			Nitrite	0.003 J	mg/L	H8507
			Methane	0.001 U	mg/L	RSK175
MW-26	30-Sep-94	0.00 -0.00	Dissolved Oxygen	6.8 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238

TABLE A.7
GROUNDWATER DATA FOR OTHER RELAVENT ANALYSES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Iron, Total	0.08 J	mg/L	H8008
			Nitrate	2.5 J	mg/L	H8039
			Sulfate	492.3 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.04 J	mg/L	H8146
			Carbon Dioxide	30 J	mg/L	H8223
			Nitrite	0.01 J	mg/L	H8507
MW-27	4-Oct-94	0.00 -0.00	Dissolved Oxygen	8.65 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.03 J	mg/L	H8008
			Nitrate	0.7 J	mg/L	H8039
			Sulfate	2860 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.02 J	mg/L	H8146
			Carbon Dioxide	30 J	mg/L	H8223
			Nitrite	0.001 J	mg/L	H8507
MW-28	1-Oct-94	0.00 -0.00	Dissolved Oxygen	0.07 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.03 J	mg/L	H8008
			Nitrate	1.4 J	mg/L	H8039
			Sulfate	0.19 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.05 J	mg/L	H8146
			Carbon Dioxide	30 J	mg/L	H8223
			Nitrite	0.005 UJ	mg/L	H8507
MW-29	2-Oct-94	0.00 -0.00	Carbon Dioxide	576	mg/L	COU-02
			Total Organic Carbon	11.2	mg/L	E415.1
			Dissolved Oxygen	0.08 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.027 J	mg/L	H8008
			Nitrate	1.4 J	mg/L	H8039
			Sulfate	3.21 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.14 J	mg/L	H8146
			Carbon Dioxide	45 J	mg/L	H8223
			Nitrite	0.001 J	mg/L	H8507
			Methane	0.001 U	mg/L	RSK175
MW-3	24-Aug-94	0.00 -0.00	Dissolved Oxygen	0.3 J	mg/L	FDO
			Iron, Total	3.16 J	mg/L	H8008
			Nitrate	2.6 J	mg/L	H8039
			Sulfate	3.73 J	mg/L	H8051

TABLE A.7
GROUNDWATER DATA FOR OTHER RELAVENT ANALYSES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Hydrogen Sulfide	0.3 J	mg/L	H8131
			Iron, Ferrous	1.94 J	mg/L	H8146
			Carbon Dioxide	80 J	mg/L	H8223
			Nitrite	0.036 J	mg/L	H8507
MW-30	1-Oct-94	0.00 -0.00	Dissolved Oxygen	0.4 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.03 J	mg/L	H8008
			Nitrate	1.3 J	mg/L	H8039
			Sulfate	258.4 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.02 J	mg/L	H8146
			Carbon Dioxide	45 J	mg/L	H8223
			Nitrite	0.013 J	mg/L	H8507
MW-31	2-Oct-94	0.00 -0.00	Dissolved Oxygen	0.12 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.68 J	mg/L	H8008
			Nitrate	1.7 J	mg/L	H8039
			Sulfate	0.96 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.28 J	mg/L	H8146
			Carbon Dioxide	35 J	mg/L	H8223
			Nitrite	0.001 J	mg/L	H8507
MW-32	4-Oct-94	0.00 -0.00	Carbon Dioxide	224	mg/L	COU-02
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.024 UJ	mg/L	H8008
			Nitrate	1.1 J	mg/L	H8039
			Sulfate	1480 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.024 UJ	mg/L	H8146
			Carbon Dioxide	25 J	mg/L	H8223
			Nitrite	0.018 J	mg/L	H8507
			Methane	0.001 U	mg/L	RSK175
MW-33	2-Oct-94	0.00 -0.00	Dissolved Oxygen	2.32 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.15 J	mg/L	H8008
			Nitrate	0.9 J	mg/L	H8039
			Sulfate	57.56 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.11 J	mg/L	H8146
			Carbon Dioxide	20 J	mg/L	H8223
			Nitrite	0.014 J	mg/L	H8507

TABLE A.7
GROUNDWATER DATA FOR OTHER RELAVENT ANALYSES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-34	3-Oct-94	0.00 -0.00	Carbon Dioxide	609	mg/L	COU-02
			Dissolved Oxygen	0.37 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.31 J	mg/L	H8008
			Nitrate	2.1 J	mg/L	H8039
			Sulfate	3.01 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.21 J	mg/L	H8146
			Carbon Dioxide	30 J	mg/L	H8223
			Nitrite	0.2 J	mg/L	H8507
			Methane	0.001 U	mg/L	RSK175
MW-35	3-Oct-94	0.00 -0.00	Carbon Dioxide	579	mg/L	COU-02
			Dissolved Oxygen	0.36 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.85 J	mg/L	H8008
			Nitrate	0.7 J	mg/L	H8039
			Sulfate	0.1 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.68 J	mg/L	H8146
			Carbon Dioxide	35 J	mg/L	H8223
			Nitrite	0.002 J	mg/L	H8507
			Methane	0.001 U	mg/L	RSK175
MW-39	5-Oct-94	0.00 -0.00	Carbon Dioxide	803	mg/L	COU-02
			Dissolved Oxygen	0.25 J	mg/L	FDO
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.09 J	mg/L	H8008
			Nitrate	8.8 J	mg/L	H8039
			Sulfate	2.97 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.07 J	mg/L	H8146
			Carbon Dioxide	45 J	mg/L	H8223
			Nitrite	0.01 J	mg/L	H8507
			Methane	0.004 J	mg/L	RSK175
MW-40	5-Oct-94	0.00 -0.00	Total Organic Carbon	46.4	mg/L	E415.1
			Sulfide	0.024 UJ	mg/L	H2238
			Iron, Total	0.02 J	mg/L	H8008
			Nitrate	0.4 J	mg/L	H8039
			Sulfate	0.81 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.04 J	mg/L	H8146
			Carbon Dioxide	55 J	mg/L	H8223

TABLE A.7
GROUNDWATER DATA FOR OTHER RELAVENT ANALYSES
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Nitrite	0.019 J	mg/L	H8507
MW-5	26-Aug-94	0.00 -0.00	Dissolved Oxygen	1.9 J	mg/L	FDO
			Iron, Total	2.53 J	mg/L	H8008
			Nitrate	0.066 UJ	mg/L	H8039
			Sulfate	52.8 J	mg/L	H8051
			Hydrogen Sulfide	0.024 UJ	mg/L	H8131
			Iron, Ferrous	1.6 J	mg/L	H8146
			Carbon Dioxide	35 J	mg/L	H8223
			Nitrite	0.004 J	mg/L	H8507
MW-6	25-Aug-94	0.00 -0.00	Dissolved Oxygen	2.5 J	mg/L	FDO
			Iron, Total	0.97 J	mg/L	H8008
			Nitrate	22.1 J	mg/L	H8039
			Sulfate	64.59 J	mg/L	H8051
			Hydrogen Sulfide	0.1 J	mg/L	H8131
			Iron, Ferrous	0.28 J	mg/L	H8146
			Carbon Dioxide	50 J	mg/L	H8223
			Nitrite	0.008 J	mg/L	H8507

[a/] Sample Interval in feet below ground surface

[b/] J = Estimated Concentration of Analyte

[c/] U = Analyte Not Detected Above Method Detection Limit

TABLE A.8
FIELD MEASUREMENTS ON GROUNDWATER
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-1	24-Aug-94	0.00 -0.00	Temperature	12 J [b/]	°C	FTEMP
			Alkalinity, Carbonate	360 J	mg/L	H8221
MW-13	25-Aug-94	0.00 -0.00	Electrical Conductivity	0.937 J	mmhos/cm	FCOND
			pH	8.12 J	pH units	FPH
			Temperature	12 J	°C	FTEMP
			Alkalinity, Carbonate	420 J	mg/L	H8221
MW-14	25-Aug-94	0.00 -0.00	Electrical Conductivity	7.22 J	mmhos/cm	FCOND
			Hardness as CaCO3	164 J	mg/L	FHARD
			pH	6.5 J	pH units	FPH
			Temperature	18 J	°C	FTEMP
			Alkalinity, Carbonate	220 J	mg/L	H8221
MW-15	25-Aug-94	0.00 -0.00	Electrical Conductivity	3.31 J	mmhos/cm	FCOND
			pH	7.47 J	pH units	FPH
			Temperature	11 J	°C	FTEMP
MW-16	25-Aug-94	0.00 -0.00	Electrical Conductivity	0.87 J	mmhos/cm	FCOND
			pH	7.6 J	pH units	FPH
			Temperature	14 J	°C	FTEMP
			Alkalinity, Carbonate	520 J	mg/L	H8221
MW-17	26-Aug-94	0.00 -0.00	Electrical Conductivity	1.25 J	mmhos/cm	FCOND
			pH	7.61 J	pH units	FPH
			Temperature	12.5 J	°C	FTEMP
			Alkalinity, Carbonate	760 J	mg/L	H8221
MW-18	26-Aug-94	0.00 -0.00	Electrical Conductivity	3.03 J	mmhos/cm	FCOND
			pH	7.31 J	pH units	FPH
			Temperature	11 J	°C	FTEMP
			Alkalinity, Carbonate	380 J	mg/L	H8221
MW-19	26-Aug-94	0.00 -0.00	Electrical Conductivity	5.97 J	mmhos/cm	FCOND
			pH	7.9 J	pH units	FPH
			Temperature	18.5 J	°C	FTEMP
			Alkalinity, Carbonate	560 J	mg/L	H8221
MW-2	24-Aug-94	0.00 -0.00	Electrical Conductivity	1.08 J	mmhos/cm	FCOND
			pH	7.48 J	pH units	FPH
			Temperature	11.5 J	°C	FTEMP
			Alkalinity, Carbonate	660 J	mg/L	H8221
MW-20	26-Aug-94	0.00 -0.00	Electrical Conductivity	2.42 J	mmhos/cm	FCOND
			pH	7.65 J	pH units	FPH
			Temperature	11 J	°C	FTEMP
			Alkalinity, Carbonate	580 J	mg/L	H8221
MW-21	26-Aug-94	0.00 -0.00	Electrical Conductivity	1.56 J	mmhos/cm	FCOND
			pH	7.58 J	pH units	FPH
			Temperature	12.5 J	°C	FTEMP

TABLE A.8
FIELD MEASUREMENTS ON GROUNDWATER
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-3	24-Aug-94	0.00 -0.00	Electrical Conductivity	1.19 J	mmhos/cm	FCOND
			pH	8.35 J	pH units	FPH
			Temperature	12 J	°C	FTEMP
			Alkalinity, Carbonate	660 J	mg/L	H8221
MW-30	1-Oct-94	0.00 -0.00	pH	7.3	pH units	E150.1
			Electrical Conductivity	1.33 J	mmhos/cm	FCOND
			pH	7.26 J	pH units	FPH
			Redox potential	6.3895 J	pE units	FREDOX
			Temperature	10.6 J	°C	FTEMP
			Alkalinity, Carbonate	140 J	mg/L	H8221
MW-31	2-Oct-94	0.00 -0.00	pH	7.6	pH units	E150.1
			Electrical Conductivity	1.08 J	mmhos/cm	FCOND
			pH	7.39 J	pH units	FPH
			Redox potential	6.7985 J	pE units	FREDOX
			Temperature	11.7 J	°C	FTEMP
			Alkalinity, Carbonate	140 J	mg/L	H8221
MW-32	4-Oct-94	0.00 -0.00	pH	7.65	pH units	E150.1
			Electrical Conductivity	3.12 J	mmhos/cm	FCOND
			Redox potential	5.6322 J	pE units	FREDOX
			Temperature	10.7 J	°C	FTEMP
			Alkalinity, Carbonate	55 J	mg/L	H8221
MW-33	2-Oct-94	0.00 -0.00	pH	7.68	pH units	E150.1
			Electrical Conductivity	0.479 J	mmhos/cm	FCOND
			pH	7.85 J	pH units	FPH
			Redox potential	4.5369 J	pE units	FREDOX
			Temperature	10.8 J	°C	FTEMP
			Alkalinity, Carbonate	55 J	mg/L	H8221
MW-34	3-Oct-94	0.00 -0.00	pH	7.63	pH units	E150.1
			Electrical Conductivity	1.09 J	mmhos/cm	FCOND
			pH	7.61 J	pH units	FPH
			Redox potential	5.5612 J	pE units	FREDOX
			Temperature	10.7 J	°C	FTEMP
			Alkalinity, Carbonate	150 J	mg/L	H8221
MW-35	3-Oct-94	0.00 -0.00	pH	7.4	pH units	E150.1
			Electrical Conductivity	1.04 J	mmhos/cm	FCOND
			pH	7.16 J	pH units	FPH
			Redox potential	5.426 J	pE units	FREDOX
			Temperature	10.9 J	°C	FTEMP
			Alkalinity, Carbonate	150 J	mg/L	H8221
MW-39	5-Oct-94	0.00 -0.00	pH	7.5	pH units	E150.1
			Electrical Conductivity	1.49 J	mmhos/cm	FCOND

TABLE A.8
FIELD MEASUREMENTS ON GROUNDWATER
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Alkalinity, Carbonate	520 J	mg/L	H8221
MW-22	26-Aug-94	0.00 -0.00	Electrical Conductivity	5.28 J	mmhos/cm	FCOND
			pH	7.76 J	pH units	FPH
			Temperature	12 J	°C	FTEMP
			Alkalinity, Carbonate	480 J	mg/L	H8221
MW-23	25-Aug-94	0.00 -0.00	Electrical Conductivity	4.52 J	mmhos/cm	FCOND
			pH	6.86 J	pH units	FPH
			Temperature	12 J	°C	FTEMP
			Alkalinity, Carbonate	300 J	mg/L	H8221
MW-24	26-Aug-94	0.00 -0.00	Electrical Conductivity	1.39 J	mmhos/cm	FCOND
			pH	7.46 J	pH units	FPH
			Temperature	11.5 J	°C	FTEMP
			Alkalinity, Carbonate	620 J	mg/L	H8221
MW-25	30-Sep-94	0.00 -0.00	pH	7.48	pH units	E150.1
			Electrical Conductivity	1.06 J	mmhos/cm	FCOND
			pH	7.48 J	pH units	FPH
			Redox potential	7.6843 J	pE units	FREDOX
			Temperature	13.6 J	°C	FTEMP
			Alkalinity, Carbonate	155 J	mg/L	H8221
MW-26	30-Sep-94	0.00 -0.00	pH	7.5	pH units	E150.1
			Electrical Conductivity	1.68 J	mmhos/cm	FCOND
			pH	7.53 J	pH units	FPH
			Redox potential	8.1643 J	pE units	FREDOX
			Temperature	10.7 J	°C	FTEMP
			Alkalinity, Carbonate	115 J	mg/L	H8221
MW-27	4-Oct-94	0.00 -0.00	pH	7.53	pH units	E150.1
			Electrical Conductivity	3.94 J	mmhos/cm	FCOND
			Redox potential	6.3387 J	pE units	FREDOX
			Temperature	10.2 J	°C	FTEMP
			Alkalinity, Carbonate	65 J	mg/L	H8221
MW-28	1-Oct-94	0.00 -0.00	pH	7.49	pH units	E150.1
			Electrical Conductivity	1.054 J	mmhos/cm	FCOND
			pH	7.34 J	pH units	FPH
			Redox potential	7.1163 J	pE units	FREDOX
			Temperature	11.2 J	°C	FTEMP
			Alkalinity, Carbonate	150 J	mg/L	H8221
MW-29	2-Oct-94	0.00 -0.00	pH	7.45	pH units	E150.1
			Electrical Conductivity	1.07 J	mmhos/cm	FCOND
			pH	7.29 J	pH units	FPH
			Temperature	11.8 J	°C	FTEMP
			Alkalinity, Carbonate	150 J	mg/L	H8221

TABLE A.8
FIELD MEASUREMENTS ON GROUNDWATER
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
			Redox potential	5.4091 J	pE units	FREDOX
			Temperature	12.7 J	°C	FTEMP
			Alkalinity, Carbonate	150 J	mg/L	H8221
MW-40	5-Oct-94	0.00 -0.00	pH	7.23	pH units	E150.1
			Electrical Conductivity	0.972 J	mmhos/cm	FCOND
			Redox potential	4.5149 J	pE units	FREDOX
			Temperature	13.2 J	°C	FTEMP
MW-5	26-Aug-94	0.00 -0.00	Electrical Conductivity	3.15 J	mmhos/cm	FCOND
			pH	7.68 J	pH units	FPH
			Temperature	12 J	°C	FTEMP
MW-6	25-Aug-94	0.00 -0.00	Electrical Conductivity	1.86 J	mmhos/cm	FCOND
			pH	7.64 J	pH units	FPH
			Redox potential	6.9506 J	pE units	FREDOX
			Temperature	11.5 J	°C	FTEMP
			Alkalinity, Carbonate	1400 J	mg/L	H8221

[a/] Sample Interval in feet below ground surface

[b/] J = Estimated Concentration of Analyte

TABLE A.9
DATA FROM FREE PRODUCT ANALYSIS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval [a/] (begining-ending)	Analyte	Result	Units	Analytical Method
MW-6	4-Oct-94	0.00 -0.00	Total Extractable Hydrocarbons	670000	mg/L	M8015
			Total Volatile Hydrocarbons	1800	mg/L	M8015
MW-6	20-Dec-94	0.00 -0.00	Total Extractable Hydrocarbons	370000	mg/L	M8015
			Total Volatile Hydrocarbons	750000	mg/L	M8015
			Benzene	520000 J [b/]	μg/L	SW8020
			Toluene	350000 J	μg/L	SW8020
			Ethylbenzene	2200000	μg/L	SW8020
			Xylenes (Total)	19000000	μg/L	SW8020
			1,3,5-Trimethylbenzene	6000000	μg/L	SW8020
			1,2,4-Trimethylbenzene	12000000	μg/L	SW8020
			1,2,3-Trimethylbenzene	800000 J	μg/L	SW8020
			Chlorobenzene	260000 J	μg/L	SW8020

[a/] Sample Interval in feet below ground surface

[b/] J = Estimated Concentration of Analyte

EVERGREEN ANALYTICAL, INC.
4036 Youngfield Wheat Ridge CO 80033
(303)425-6021

GCMS CONFIRMATION

ient Sample Number : MW-26-W
b Sample Number : X95675
Date Sampled : 09/30/94
Date Received : 10/05/94
Date Extracted/Prepared : 10/12/94
Date Analyzed : 10/12/94

Client I.D. : ELLWSWORTH AFB
Lab Project No. : 94-3803
Effective Dilution : 1.00
Method : 8240(8260)
Matrix : WATER
Lab File No. : >L9327
Method Blank No. : RB101294A

Compound Name	Cas Number	Conc. ug/L	PQL* ug/L
Benzene	71-43-2	U	5
Toluene	108-88-3	U	5
Ethyl Benzene	100-41-4	U	5
Total Xylenes	1330-20-7	U	5
Chlorobenzene	108-90-7	U	5
1,2,4-Trimethylbenzene	95-63-6	UX	5
1,2,3-Trimethylbenzene	526-73-8	UX	5
1,3,5-Trimethylbenzene (Mesitylene)	108-67-8	UX	5

Surrogate Recoveries:		QC Limits
1,2 Dichloroethane-d4	98%	(83-112)
Toluene-d8	97%	(93-104)
Bromofluorobenzene	96%	(87-105)

Qualifiers:
X = Concentration estimated. No daily calibration.
U = Compound analyzed for, but not detected above the reporting limit(0.2 ppb) Reporting limits are roughly the method detection limits in reagent water.
J = Indicates an estimated value when the compound is detected, but is below the Practical Quantitation Limit (PQL).
B = Compound found in blank and sample. Compare blank and sample data.
E = Compound is detected at a concentration outside the calibration limits.
* = Practical Quantitation Limits listed are approximately 10 times the detection limits for reagent water.
Unless otherwise noted all concentrations and PQL's for soils are quantitated on an as is basis.
NA = Not applicable or not available

Analyst

Approved

EVERGREEN ANALYTICAL, INC.
4036 Youngfield Wheat Ridge CO 80033
(303)425-6021

GCMS CONFIRMATION

Client Sample Number	: MW-25-W	Client I.D.	: ELLWSWORTH
Lab Sample Number	: X95674	Lab Project No.	: 94-3803
Date Sampled	: 09/30/94	Effective Dilution	: 1.00
Date Received	: 10/05/94	Method	: 8240(8260)
Date Extracted/Prepared	: 10/12/94	Matrix	: WATER
Date Analyzed	: 10/12/94	Lab File No.	: >L9326
		Method Blank No.	: RB101294A

Compound Name	Cas Number	Conc. ug/L	PQL* ug/L
Benzene	71-43-2	0.4 J	5
Toluene	108-88-3	0.3 J	5
Ethyl Benzene	100-41-4	U	5
Total Xylenes	1330-20-7	U	5
Chlorobenzene	108-90-7	U	5
1,2,4-Trimethylbenzene	95-63-6	UX	5
1,2,3-Trimethylbenzene	526-73-8	UX	5
1,3,5-Trimethylbenzene (Mesitylene)	108-67-8	UX	5

Surrogate Recoveries:		QC Limits
1,2 Dichloroethane-d4	97%	(83-112)
Toluene-d8	98%	(93-104)
Bromofluorobenzene	97%	(87-105)

Qualifiers:
X = Concentration estimated. No daily calibration.
U = Compound analyzed for, but not detected above the reporting limit(0.2 pp
Reporting limits are roughly the method detection limits in reagent wate
J = Indicates an estimated value when the compound is detected, but is below the Practical Quantitation Limit (PQL).
B = Compound found in blank and sample. Compare blank and sample data.
E = Compound is detected at a concentration outside the calibration limits.
* = Practical Quantitation Limits listed are approximately 10 times the detection limits for reagent water.
Unless otherwise noted all concentrations and PQL's for soils are quantitated on an as is basis.
NA = Not applicable or not available

Analyst

Approved

TABLE A.10
QA/QC WATER BLANK RESULTS
AND EQUIPMENT BLANK ASSOCIATIONS
RMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

RESULTS OF QA/QC WATER BLANK SAMPLES

Sample Name	Sample Date	Matrix	Analytica Method	Analyte	Result
Equipment Blank1	20-Sep-94	WQ	SW8020	Benzene	0.4 U
Equipment Blank1	20-Sep-94	WQ	SW8020	Toluene	4 U
Equipment Blank1	20-Sep-94	WQ	SW8020	Ethylbenzene	4 U
Equipment Blank1	20-Sep-94	WQ	SW8020	1,2,3-Trimethylbenzene	4 U
Equipment Blank1	20-Sep-94	WQ	SW8020	1,2,4-Trimethylbenzene	4 U
Equipment Blank1	20-Sep-94	WQ	SW8020	1,3,5-Trimethylbenzene	4 U
Equipment Blank1	20-Sep-94	WQ	SW8020	Xylenes	4 U
Equipment Blank2	03-Oct-94	WQ	SW8020	Benzene	0.4 U
Equipment Blank2	03-Oct-94	WQ	SW8020	Toluene	4 U
Equipment Blank2	03-Oct-94	WQ	SW8020	Ethylbenzene	4 U
Equipment Blank2	03-Oct-94	WQ	SW8020	1,2,3-Trimethylbenzene	4 U
Equipment Blank2	03-Oct-94	WQ	SW8020	1,2,4-Trimethylbenzene	4 U
Equipment Blank2	03-Oct-94	WQ	SW8020	1,3,5-Trimethylbenzene	4 U
Equipment Blank2	03-Oct-94	WQ	SW8020	Xylenes	4 U
Equipment Blank3	20-Sep-94	WQ	SW8020	Benzene	0.4 U
Equipment Blank3	20-Sep-94	WQ	SW8020	Toluene	4 U
Equipment Blank3	20-Sep-94	WQ	SW8020	Ethylbenzene	4 U
Equipment Blank3	20-Sep-94	WQ	SW8020	1,2,3-Trimethylbenzene	4 U
Equipment Blank3	20-Sep-94	WQ	SW8020	1,2,4-Trimethylbenzene	4 U
Equipment Blank3	20-Sep-94	WQ	SW8020	1,3,5-Trimethylbenzene	4 U
Equipment Blank3	20-Sep-94	WQ	SW8020	Xylenes	0.4 J
Equipment Blank4	05-Oct-94	WQ	SW8020	Benzene	0.4 U
Equipment Blank4	05-Oct-94	WQ	SW8020	Toluene	4 U
Equipment Blank4	05-Oct-94	WQ	SW8020	Ethylbenzene	4 U
Equipment Blank4	05-Oct-94	WQ	SW8020	1,2,3-Trimethylbenzene	4 U
Equipment Blank4	05-Oct-94	WQ	SW8020	1,2,4-Trimethylbenzene	4 U
Equipment Blank4	05-Oct-94	WQ	SW8020	1,3,5-Trimethylbenzene	4 U
Equipment Blank4	05-Oct-94	WQ	SW8020	Xylenes	4 U
Equipment Blank5	22-Sep-94	WQ	SW8020	Benzene	0.4 U
Equipment Blank5	22-Sep-94	WQ	SW8020	Toluene	0.7
Equipment Blank5	22-Sep-94	WQ	SW8020	Ethylbenzene	4 U
Equipment Blank5	22-Sep-94	WQ	SW8020	1,2,3-Trimethylbenzene	4 U
Equipment Blank5	22-Sep-94	WQ	SW8020	1,2,4-Trimethylbenzene	4 U
Equipment Blank5	22-Sep-94	WQ	SW8020	1,3,5-Trimethylbenzene	4 U
Equipment Blank5	22-Sep-94	WQ	SW8020	Xylenes	4 U
Equipment Blank6	23-Sep-94	WQ	SW8020	Benzene	67
Equipment Blank6	23-Sep-94	WQ	SW8020	Toluene	2.6
Equipment Blank6	23-Sep-94	WQ	SW8020	Ethylbenzene	15
Equipment Blank6	23-Sep-94	WQ	SW8020	1,2,3-Trimethylbenzene	45
Equipment Blank6	23-Sep-94	WQ	SW8020	1,2,4-Trimethylbenzene	55
Equipment Blank6	23-Sep-94	WQ	SW8020	1,3,5-Trimethylbenzene	29
Equipment Blank6	23-Sep-94	WQ	SW8020	Xylenes	150
Trip Blank1	21-Sep-94	WQ	SW8020	Benzene	0.4 U
Trip Blank1	21-Sep-94	WQ	SW8020	Toluene	0.6
Trip Blank1	21-Sep-94	WQ	SW8020	Ethylbenzene	4 U
Trip Blank1	21-Sep-94	WQ	SW8020	1,2,3-Trimethylbenzene	4 U
Trip Blank1	21-Sep-94	WQ	SW8020	1,2,4-Trimethylbenzene	4 U
Trip Blank1	21-Sep-94	WQ	SW8020	1,3,5-Trimethylbenzene	4 U
Trip Blank1	21-Sep-94	WQ	SW8020	Xylenes	4 U
Trip Blank1	03-Oct-94	WQ	SW8020	Benzene	0.4 U
Trip Blank1	03-Oct-94	WQ	SW8020	Toluene	4 U
Trip Blank1	03-Oct-94	WQ	SW8020	Ethylbenzene	4 U
Trip Blank1	03-Oct-94	WQ	SW8020	1,2,3-Trimethylbenzene	4 U
Trip Blank1	03-Oct-94	WQ	SW8020	1,2,4-Trimethylbenzene	4 U
Trip Blank1	03-Oct-94	WQ	SW8020	1,3,5-Trimethylbenzene	4 U

TABLE A.10
QA/QC WATER BLANK RESULTS
AND EQUIPMENT BLANK ASSOCIATIONS
RMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

RESULTS OF QA/QC WATER BLANK SAMPLES

Sample Name	Sample Date	Matrix	Analytica Method	Analyte	Result
Equipment Blank1	20-Sep-94	WQ	SW8020	Benzene	0.4 U
Trip Blank1	03-Oct-94	WQ	SW8020	Xylenes	4 U
Trip Blank1	05-Oct-94	WQ	SW8020	Benzene	0.4 U
Trip Blank1	05-Oct-94	WQ	SW8020	Toluene	4 U
Trip Blank1	05-Oct-94	WQ	SW8020	Ethylbenzene	4 U
Trip Blank1	05-Oct-94	WQ	SW8020	1,2,3-Trimethylbenzene	4 U
Trip Blank1	05-Oct-94	WQ	SW8020	1,2,4-Trimethylbenzene	4 U
Trip Blank1	05-Oct-94	WQ	SW8020	1,3,5-Trimethylbenzene	4 U
Trip Blank1	05-Oct-94	WQ	SW8020	Xylenes	4 U

PRIMARY SAMPLES ASSOCIATED WITH EQUIPMENT RINSEATE BLANKS

Sample Name	Associated Water Blank	Sample Date	Matrix	Sample Interval (ft bgs: beginning-ending)	Analytical Method
MW-25	Equipment Blank3	12-Sep-94	SO	14.5 - 15.5	SW8020
MW-26	Equipment Blank3	13-Sep-94	SO	23.5 - 24.5	SW8020
MW-27	Equipment Blank3	14-Sep-94	SO	23.5 - 24.5	SW8020
MW-28	Equipment Blank3	14-Sep-94	SO	18.5 - 19.5	SW8020
MW-29	Equipment Blank3	15-Sep-94	SO	16.5 - 17.5	SW8020
MW-30	Equipment Blank3	15-Sep-94	SO	19.5 - 20.5	SW8020
MW-31	Equipment Blank3	16-Sep-94	SO	20.5 - 21.5	SW8020
MW-32	Equipment Blank3	19-Sep-94	SO	17.5 - 18.5	SW8020
MW-33	Equipment Blank3	19-Sep-94	SO	22.5 - 23.5	SW8020
MW-34	Equipment Blank3	20-Sep-94	SO	24.5 - 25.5	SW8020
MW-35	Equipment Blank3	20-Sep-94	SO	21.5 - 22.5	SW8020
MW-36	Equipment Blank3	21-Sep-94	SO	21.5 - 22.5	SW8020
MW-37	Equipment Blank3	21-Sep-94	SO	21.5 - 22.5	SW8020
MW-39	Equipment Blank3	22-Sep-94	SO	18.5 - 19.5	SW8020
MW-40	Equipment Blank5	23-Sep-94	SO	13.5 - 14.5	SW8020
MW-40	Equipment Blank3	23-Sep-94	SO	13.5 - 14.5	SW8020
SB-1	Equipment Blank3	27-Aug-94	SO	16.5 - 17.5	SW8020
SB-3	Equipment Blank3	27-Aug-94	SO	9 - 10	SW8020
SB-6	Equipment Blank3	27-Aug-94	SO	22.5 - 23.5	SW8020
SC-1-1	Equipment Blank3	28-Sep-94	DC	NA	SW8020
SC-1-2	Equipment Blank3	28-Sep-94	DC	NA	SW8020
SC-2-1	Equipment Blank3	28-Sep-94	DC	NA	SW8020
SC-2-2	Equipment Blank3	28-Sep-94	DC	NA	SW8020

TABLE A.11
DATA VALIDATION QUALIFIER APPLICATION
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval ft bgs: beginning-ending	Martix	Analytical Method	Analyte	Laboratory Result[a/]	Holding Time Flag[b/]	Method Blank Flag[c/]	PQL Flag[d/]	Field Flag[e/]	Final Report
MW-26	13-Sep-94	23.5 - 24.5	Soil	SW9060	Total Organic Carbon	=			J		J
MW-29	15-Sep-94	16.5 - 17.5	Soil	SW8020	Toluene	=			J		J
				SW8020	Ethylbenzene	=			J		J
				SW8020	1,2,3-Trimethylbenzene	=			J		J
MW-30	15-Sep-94	19.5 - 20.5	Soil	SW8020	Benzene	=			J		J
				SW8020	Toluene	=			J		J
				SW8020	Ethylbenzene	=			J		J
				SW8020	Xylenes (Total)	=			J		J
				SW8020	1,3,5-Trimethylbenzene	=			J		J
				SW8020	1,2,3-Trimethylbenzene	=			J		J
MW-32	19-Sep-94	17.5 - 18.5	Soil	SW8020	Toluene	=		U	J		U
				SW8020	Xylenes (Total)	=			J	U	U
MW-33	19-Sep-94	22.5 - 23.5	Soil	SW8020	Toluene	=		U	J		U
				SW8020	Xylenes (Total)	=			J	U	U
MW-34	20-Sep-94	24.5 - 25.5	Soil	SW8020	Benzene	=			J		J
MW-35	20-Sep-94	21.5 - 22.5	Soil	SW8020	Toluene	=			J		J
				SW8020	1,3,5-Trimethylbenzene	=			J		J
				SW8020	1,2,4-Trimethylbenzene	=			J		J
MW-36	21-Sep-94	21.5 - 22.5	Soil	SW8020	Benzene	ND	R				R
				SW8020	Toluene	=		U			U
				SW8020	Toluene	=			J	U	U
				SW8020	Ethylbenzene	=	R				R
				SW8020	Ethylbenzene	=			J		J
				SW8020	Xylenes (Total)	=	R				R
				SW8020	Xylenes (Total)	=			J		J
				SW8020	1,3,5-Trimethylbenzene	=			J		J
				SW8020	1,2,4-Trimethylbenzene	=			J		J
				SW8020	1,2,3-Trimethylbenzene	=			J		J
MW-37	21-Sep-94	21.5 - 22.5	Soil	SW8020	Benzene	=			J		J

TABLE A.11
DATA VALIDATION QUALIFIER APPLICATION
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval ft bgs: beginning-ending	Martix	Analytical Method	Analyte	Laboratory Result$^{a/}$	Holding Time Flag$^{b/}$	Method Blank Flag$^{c/}$	PQL Flag$^{d/}$	Field Flag$^{e/}$	Final Report
MW-39	22-Sep-94	18.5 - 19.5	Soil	SW8020	Toluene	=			J		J
SB-1	27-Aug-94	16.5 - 17.5	Soil	SW8020	Ethylbenzene	=			J		J
				SW8020	Xylenes (Total)	=			J		J
				SW8020	1,3,5-Trimethylbenzene	=			J		J
				SW8020	1,2,4-Trimethylbenzene	=			J		J
				SW8020	1,2,3-Trimethylbenzene	=			J		J
SC-1-1	28-Sep-94	composite	Soil	SW8020	Benzene	=			J		J
SC-1-2	28-Sep-94	composite	Soil	SW8020	Benzene	=			J		J
SC-2-1	28-Sep-94	composite	Soil	SW8020	Xylenes (Total)	=		U	J	U	U
				SW8020	1,3,5-Trimethylbenzene	=			J		J
				SW8020	1,2,4-Trimethylbenzene	=			J		J
				SW8020	1,2,3-Trimethylbenzene	=			J		J
SC-2-2	28-Sep-94	composite	Soil	SW8020	Benzene	=			J		J
				SW8020	Ethylbenzene	=			J		J
				SW8020	Xylenes (Total)	=		U	J		U
				SW8020	1,3,5-Trimethylbenzene	=			J		J
				SW8020	1,2,4-Trimethylbenzene	=			J		J
				SW8020	1,2,3-Trimethylbenzene	=			J		J
FIELDQC EB1	20-Sep-94	0 - 0	Water	SW8020	Toluene	=		U			U
FIELDQC EB3	20-Sep-94	0 - 0	Water	SW8020	Toluene	=		U			U
FIELDQC TB1	05-Oct-94	0 - 0	Water	SW8020	Toluene	=		U			U
MW-6	25-Aug-94	0 - 0	Water	SW8020	Toluene	=			J		J
MW-25	30-Sep-94	0 - 0	Water	SW8020	1,2,4-Trimethylbenzene	=			J		J
MW-28	01-Oct-94	0 - 0	Water	SW8020	Benzene	=			J		J
				SW8020	Ethylbenzene	=			J		J
				SW8020	Xylenes (Total)	=			J		J
				SW8020	1,2,4-Trimethylbenzene	=			J		J
				SW8020	1,2,3-Trimethylbenzene	=			J		J
MW-29	02-Oct-94	0 - 0	Water	SW8020	Toluene	=			J		J

TABLE A.11
DATA VALIDATION QUALIFIER APPLICATION
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Sample Interval ft bgs: beginning-ending	Martix	Analytical Method	Analyte	Laboratory Result[a/]	Holding Time Flag[b/]	Method Blank Flag[c/]	PQL Flag[d/]	Field Flag[e/]	Final Report
MW-32	09-Nov-94	0 - 0	Water	SW8020	Toluene	=		U	J		U
				SW8020	Xylenes (Total)	=		U	J		U
MW-33	02-Oct-94	0 - 0	Water	SW8020	Toluene	=		U	J		U
MW-35	03-Oct-94	0 - 0	Water	SW8020	Toluene	=			J		J
MW-39	05-Oct-94	0 - 0	Water	RSK175	Methane	=			J		J
MW-41	09-Nov-94	0 - 0	Water	SW8020	Toluene	=		U	J		U

[a/] = Result reported by analytical laboratory. ND = not detected. "=" = An real value was reported.

[b/] = A flag was applied to the data because sample holding time was exceeded.

[c/] = A flag was applied because an analyte was detected during the analysis of a method blank.

[d/] = A flag was applied because the reported value was above the MDL and below the PQL.

[e/] = A flag was applied because an analyte was detected during the analysis of a field blank.

TABLE A.12
DUPLICATE AND REPLICATE SAMPLE RESULTS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sample Location	Sample Date	Matrix	Sample Interval (ft bgs: beginning-ending)	Analytical Method	Analyte	Real Sample Result	Duplicate Sample Result	Units	RPD[a/]
MW-36	21-Sep-94	Soil	21.5 - 22.5	SW8020	Benzene	0.48 U	2.4 R	µg/kg	
				SW8020	Toluene	4.8 U	24 UR	µg/kg	
				SW8020	Ethylbenzene	0.8 J	15 R	µg/kg	179
				SW8020	Xylenes (Total)	2.3 J	46 R	µg/kg	180
				SW8020	1,3,5-Trimethylbenzene	2.9 J	790	µg/kg	198
				SW8020	1,2,4-Trimethylbenzene	1.9 J	980	µg/kg	199
				SW8020	1,2,3-Trimethylbenzene	0.8 J	540 J	µg/kg	199
MW-39	22-Sep-94	Soil	18.5 - 19.5	SW8020	Benzene	2.3 U	2.2 U	µg/kg	
				SW8020	Toluene	20 J	12 J	µg/kg	50
				SW8020	Ethylbenzene	220	150	µg/kg	37
				SW8020	Xylenes (Total)	1100	870	µg/kg	23
				SW8020	1,3,5-Trimethylbenzene	1900	1900	µg/kg	
				SW8020	1,2,4-Trimethylbenzene	3500	3200	µg/kg	8.9
				SW8020	1,2,3-Trimethylbenzene	2200	2000	µg/kg	9.5
MW-35	03-Oct-94	Water	0 - 0	SW8020	Benzene	200	190	µg/L	5.1
				SW8020	Toluene	2.8 J	3.2	µg/L	13.3
				SW8020	Ethylbenzene	220	200	µg/L	9.5
				SW8020	Xylenes (Total)	550	460	µg/L	17
				SW8020	1,3,5-Trimethylbenzene	160	190	µg/L	17
				SW8020	1,2,4-Trimethylbenzene	470	360	µg/L	26
				SW8020	1,2,3-Trimethylbenzene	130	150	µg/L	14

[a/] RPD = relative percent difference between real and duplicate sample.

APPENDIX A

NARRATIVE OF DATA QUALITY REVIEW/QUALITY ASSURANCE

Soil and groundwater samples collected at Area D, Ellsworth AFB, were shipped to Evergreen Analytical Laboratory (EAL) for analysis. EAL noted that all sample containers were received as documented on the chain-of-custody except for one groundwater sample, which had been mislabeled MW-16 rather than MW-6. No containers were received unsealed, broken, unlabeled, unpreserved, or otherwise in a condition that would compromise analysis. All required matrix spike/matrix spike duplicate (MS/MSD) analyses were completed. Although one MSD sample exhibited poor surrogate recovery and low target analyte recoveries (due to a bad purge cycle), all MS results were acceptable, including all MS surrogate recoveries, which were within specified and acceptable recovery limits. Only one laboratory control sample exhibited low recoveries for the benzene, toluene, ethylbenzene, and xylenes (BTEX) compounds. Soil sample MW-36 was originally analyzed at a dilution factor of 125. A subsequent analysis at a dilution factor of 5 was completed outside of the holding time requirement. This sample has been H qualified (see preceding tables), and not used in the predictive chemical fate assessment.

APPENDIX B

GEOLOGIC BORING LOGS AND WELL COMPLETION AND DEVELOPMENT DATA

Sheet 1 of 1

GEOLOGIC BORING LOG

BORING NO.:	VW	**CONTRACTOR:**	Layne Western	**DATE SPUD:**	8/25/93
CLIENT:	Ellsworth AFB	**RIG TYPE:**	Failing	**DATE CMPL:**	
JOB NO.:	DE268.42.04	**DRLG MED:**	HS	**ELEVATION:**	
LOCATION:	Bldg. 102	**BORING DIA.:**	11"	**TEMP:**	75
GEOLOGIST	R. Frishmuth	**DRLG FLUID:**	N/A	**WEATHER:**	Clear/Windy

Depth (ft.)	Pro-file	USCS	Geologic Description	Samples		Sample Type	Blow Counts	Remarks
				No.	Depth (ft)			TIP = (isobutylene units)
1			Asphalt over concrete for approximately 1 foot. Dark brown silty					Log from cuttings
			CLAY with a trace of sand, slightly moist.					
5								no odor
			SAA					
			SAA					
			Gravel – drilling much harder.					
10			Drilling easier for 2 feet then back into gravel with some clay,					
			silt and sand.					
			GRAVEL with sand and clay					
15								
20								
25								
30								
35								
40								

sl – slight
tr – trace
sm – some
& – and
@ – at
w – with

v – very
kt – light
dk – dark
bf – buff
brn – brown
blk – black

NO/NS – no odor/ no stain
HSA – Hollow stem auger
SSA – Solid stem auger

fm – fine
m – medium
crs – coarse
BH – Bore Hole
SAA – Same As Above
M.S.L. – Mean Sea Level

☐ SPLIT SPOON SAMPLE
☐ SHELBY TUBE SAMPLE
☐ GRAB SAMPLE
EST. WATER TABLE

Sheet 1 of 1

GEOLOGIC BORING LOG

BORING NO.: MPA
CLIENT: Ellsworth AFB
JOB NO.: DE268.42.04
LOCATION: Bldg. 102
GEOLOGIST R. Frishmuth

CONTRACTOR: Layne Western
RIG TYPE: Failing
DRLG MED: HS
BORING DIA.: 8"
DRLG FLUID: N/A

DATE SPUD: 8/24/93
DATE CMPL:
ELEVATION:
TEMP: 90
WEATHER: Clear/Sunny

Depth (ft.)	Pro-file	USCS	Geologic Description	Samples No.	Samples Depth (ft)	Sample Type	Blow Counts	Remarks TIP = (isobutylene units)
1			Approximately 1' of asphalt and concrete. Dark brown silty CLAY,					Log from cuttings
			slightly moist.					
5			SAA			SS	4, 5	no odor
			SAA with some sand interbedded and a trace of gravel, slightly				7, 12	HS = 120 ppm
			plastic.					
			SAA					
			Gravel, harder drilling.					
10			SAA					
			GRAVEL with silt, clay and sand dark brown to tan.			SS	9, 12	no odor
							19, 19	HS = 120 ppm
			Dark brown silty CLAY, dirlling much easier.					
15			GRAVEL with silt and clay.			SS	30, 29	HS = 120 ppm
			Drilling hard again – auger refusal.					
20								
25								
30								
35								
40								

sl – slight
tr – trace
sm – some
& – and
@ – at
w – with

v – very
kt – light
dk – dark
bf – buff
brn – brown
blk – black

NO/NS – no odor/ no stain
HSA – Hollow stem auger
SSA – Solid stem auger

fm – fine
m – medium
crs – coarse
BH – Bore Hole
SAA – Same As Above
M.S.L. – Mean Sea Level

☐ SPLIT SPOON SAMPLE
☐ SHELBY TUBE SAMPLE
☐ GRAB SAMPLE
EST. WATER TABLE

Sheet 1 of 1

GEOLOGIC BORING LOG

BORING NO.:	MPB	**CONTRACTOR:**	Layne Western	**DATE SPUD:**	8/24/93
CLIENT:	Ellsworth AFB	**RIG TYPE:**	Failing	**DATE CMPL:**	
JOB NO.:	DE268.42.04	**DRLG MED:**	HS	**ELEVATION:**	
LOCATION:	Bldg. 102	**BORING DIA.:**	8"	**TEMP:**	90
GEOLOGIST	R. Frishmuth	**DRLG FLUID:**	N/A	**WEATHER:**	Clear/Sunny

Depth (ft.)	Pro-file	USCS	Geologic Description	Samples No.	Samples Depth (ft)	Sample Type	Blow Counts	Remarks TIP = (isobutylene units)
1			Concrete covered by asphalt to 1 foot. Dark brown silty CLAY,					Log from cuttings
			slightly moist and plastic					
5			SAA			SS	4, 5	no odor
			SAA with some sand				8, 9	HS = 120
			SAA with more clay and less sand, moist and plastic					
10			Gravel, drilling harder					
			GRAVEL pebbles 1" and some sand, silt and clay. Auger refusal at			SS	12, 19	TD=11' no odor
			11 feet.				25, 20	HS = 110
15								
20								
25								
30								
35								
40								

sl – slight
tr – trace
sm – some
& – and
@ – at
w – with

v – very
kt – light
dk – dark
bf – buff
brn – brown
blk – black

NO/NS–no odor/ no stain
HSA–Hollow stem auger
SSA–Solid stem auger

fm – fine
m – medium
crs – coarse
BH – Bore Hole
SAA – Same As Above
M.S.L. – Mean Sea Level

☐ SPLIT SPOON SAMPLE
☐ SHELBY TUBE SAMPLE
☐ GRAB SAMPLE
EST. WATER TABLE

GEOLOGIC BORING LOG

BORING NO.: VW1
CLIENT: Ellsworth AFB
JOB NO.: DE268.42.04
LOCATION: Area D
GEOLOGIST R. Frishmuth

CONTRACTOR: Layne Western
RIG TYPE: Failing
DRLG MED: HS
BORING DIA.: 11"
DRLG FLUID: N/A

DATE SPUD: 8/24/93
DATE CMPL: 8/24/93
ELEVATION: 3,250
TEMP: 70
WEATHER: Clear/Sunny

Depth (ft.)	Pro-file	USCS	Geologic Description	Samples No.	Samples Depth (ft)	Sample Type	Blow Counts	Remarks TIP = (isobutylene units)
1			Dark brown siltly CLAY with some sand, slightly moist and plastic.					Log from cuttings
			increasing clay with depth					
5			SAA					
			Brown silty CLAY with gray staining, moist and plastic. Slightly stiff.			SS		Strong odor
			Olive/gray silty CLAY with a trace of sand, moist and plastic.					HS = 1000
10			SAA					
			Tan to brown fine SAND with gray staining, slightly moist.			SS	1, 7	
							7, 8	HS = 720
			SAA					
			GRAVEL 1" pebbles and coarse sand			SS	20, 34	Strong odor
15								
			SAA					
			Auger refusal at 17'					TD = 17'
20								
25								
30								
35								
40								

sl – slight
tr – trace
sm – some
& – and
@ – at
w – with

v – very
lt – light
dk – dark
bf – buff
brn – brown
blk – black

NO/NS – no odor/ no stain
HSA – Hollow stem auger
SSA – Solid stem auger

fm – fine
m – medium
crs – coarse
BH – Bore Hole
SAA – Same As Above
M.S.L. – Mean Sea Level

☐ SPLIT SPOON SAMPLE
☐ SHELBY TUBE SAMPLE
☐ GRAB SAMPLE
EST. WATER TABLE

Sheet 1 of 1

GEOLOGIC BORING LOG

BORING NO.:	MPA	**CONTRACTOR:**	Layne Western	**DATE SPUD:**	8/23/93
CLIENT:	Ellsworth AFB	**RIG TYPE:**	Failing	**DATE CMPL:**	8/23/93
JOB NO.:	DE268.42.04	**DRLG MED:**	HS	**ELEVATION:**	3,250
LOCATION:	Area D	**BORING DIA.:**	8"	**TEMP:**	85
GEOLOGIST	R. Frishmuth	**DRLG FLUID:**	N/A	**WEATHER:**	Clear/Windy

Depth (ft.)	Pro-file	USCS	Geologic Description	Samples		Sample Type	Blow Counts	Remarks
				No.	Depth (ft)			TIP = (isobutylene units)
1			Dark brown SILT with some sand and gravel and a trace of clay,					Log from cuttings
			slightly moist.					
5			SAA					
			Brown silty CLAY, olive streaks and staining, moist, slightly			SS	2, 2	Slight odor, poor rec.
			stiff and plastic.				2, 4	HS = 2500
			Increasing moisture with depth.					
10			SAA					
			Light brown/olive fine SAND, not as stained as MPB, slightly moist.			SS	2, 5	Strong odor
							9, 10	HS = 9500
			SAA					
			SAA, increasing silt/clay with depth.			SS	2, 3	Strong odor
15			GRAVEL and coarse sand.				R	HS = 8400
								TD = 15'
20								
25								
30								
35								
40								

sl – slight
tr – trace
sm – some
& – and
@ – at
w – with

v – very
kt – light
dk – dark
bf – buff
brn – brown
blk – black

NO/NS – no odor/ no stain
HSA – Hollow stem auger
SSA – Solid stem auger

fm – fine
m – medium
crs – coarse
BH – Bore Hole
SAA – Same As Above
M.S.L. – Mean Sea Level

☐ SPLIT SPOON SAMPLE

☐ SHELBY TUBE SAMPLE

☐ GRAB SAMPLE

EST. WATER TABLE

Sheet 1 of 1

GEOLOGIC BORING LOG

BORING NO.: MPB
CLIENT: Ellsworth AFB
JOB NO.: DE268.42.04
LOCATION: Area D
GEOLOGIST R. Frishmuth

CONTRACTOR: Layne Western
RIG TYPE: Failing
DRLG MED: HS
BORING DIA.: 8"
DRLG FLUID: N/A

DATE SPUD: 8/23/93
DATE CMPL: 8/23/93
ELEVATION: 3,250
TEMP: 90
WEATHER: Clear/Windy

Depth (ft.)	Pro-file	USCS	Geologic Description	Samples		Sample Type	Blow Counts	Remarks
				No.	Depth (ft)			TIP = (isobutylene units)
1			Dark brown SAND with some silt, tough drilling, very dry					Log from cuttings
			flaky cuttings.					
								No odor
5			SAA					
			Brown SILT with some sand, increasing moisture with depth,			SS	7, 4	No odor
			very stiff.				4, 7	HS = 100
			Very silty CLAY, slightly moist and plastic.					
10			SAA			SS	3, 4	Odor
			Gray, stained silty CLAY, less moist than above.				8, 8	HS = 9500
			SAA			SS	4, 5	HS = 9000
			Light brown/olive fine SAND, slight moist.				17, R	
15			GRAVEL.					
								TD = 15'
20								
25								
30								
35								
40								

sl – slight
tr – trace
sm – some
& – and
@ – at
w – with

v – very
lt – light
dk – dark
bf – buff
brn – brown
blk – black

NO/NS–no odor/ no stain
HSA–Hollow stem auger
SSA–Solid stem auger

fm – fine
m – medium
crs – coarse
BH – Bore Hole
SAA – Same As Above
M.S.L. – Mean Sea Level

☐ SPLIT SPOON SAMPLE
☐ SHELBY TUBE SAMPLE
☐ GRAB SAMPLE
EST. WATER TABLE

Sheet 1 of 1

GEOLOGIC BORING LOG

BORING NO.: MPC
CLIENT: Ellsworth AFB
JOB NO.: DE268.42.04
LOCATION: Area D
GEOLOGIST R. Frishmuth

CONTRACTOR: Layne Western
RIG TYPE: Failing
DRLG MED: HS
BORING DIA.: 8"
DRLG FLUID: N/A

DATE SPUD: 8/23/93
DATE CMPL: 8/23/93
ELEVATION: 3,250
TEMP: 80
WEATHER: Clear/Windy

Depth (ft.)	Pro-file	USCS	Geologic Description	Samples		Sample Type	Blow Counts	Remarks TIP = (isobutylene units)
				No.	Depth (ft)			
1			Dark brown silty CLAY with some sand and gravel, slightly plastic					Log from cuttings
			and stiff.					
5			SAA					HS = 75 ppm
						SS	2, 2	2" of recovery
							5, 5	
						SS	2, 3	Full recovery
			SAA with increasing clay content.				5, 5	HS = 80 ppm
10								
						SS	3, 3	Strong POL odor
			SAA with some staining, increased clay content and moisture.				6, 11	HS = 2000 ppm
			Light brown/olive fine SAND with some gravel and silt, moist.					
			SAA			SS	3, 4	Strong POL odor
15			Coarse SAND/GRAVEL (1" and pebbles).				7, 17	HS = 4000 ppm
			Interbedded CLAY layers, gravel and coarse sand, very moist.			SS		Strong POL odor
								Refusal – HS=3500 ppm
			SAA					
			Weathered gray SHALE with iron staining along fractures.					
20						SS	6, 8	No odor
			SAA				12, 24	
								TD = 22'
25								
30								
35								
40								

sl – slight
tr – trace
sm – some
& – and
@ – at
w – with

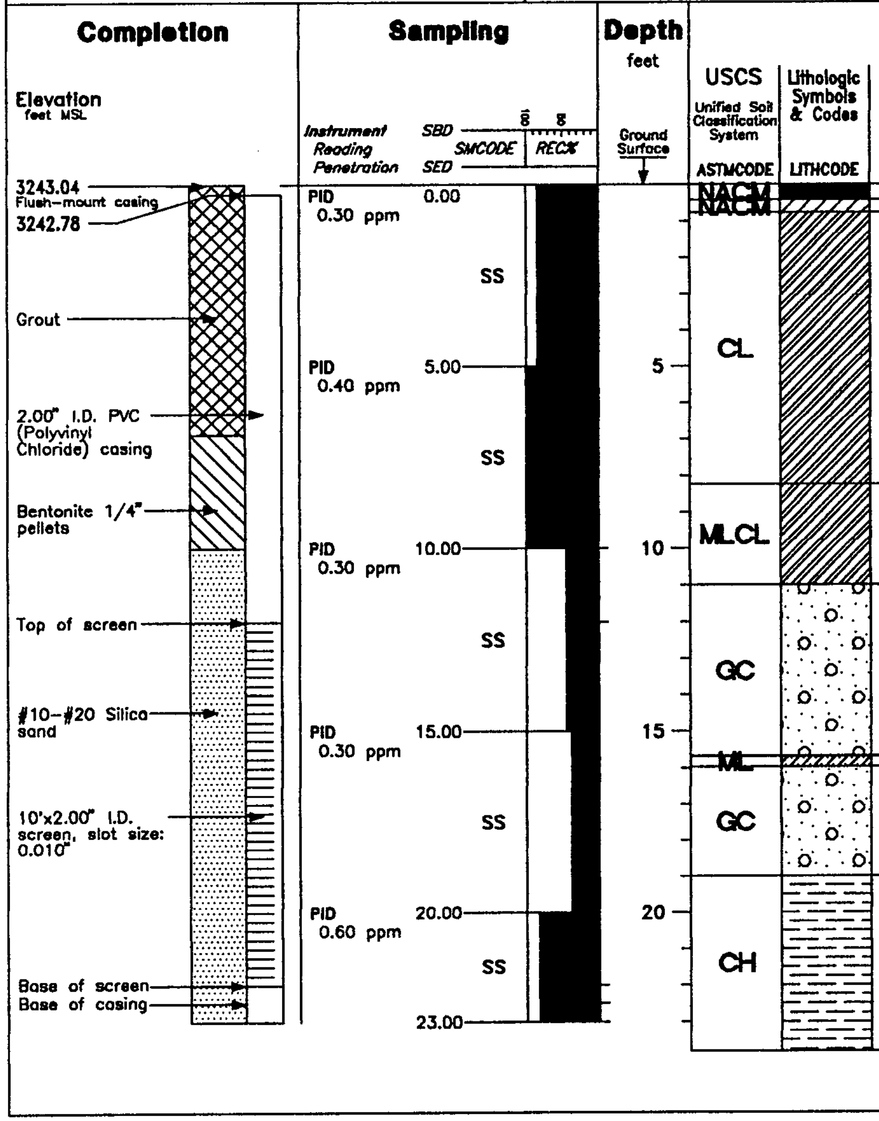
v – very
kt – light
dk – dark
bf – buff
brn – brown
blk – black

NO/NS–no odor/ no stain
HSA–Hollow stem auger
SSA–Solid stem auger

fm – fine
m – medium
crs – coarse
BH – Bore Hole
SAA – Same As Above
M.S.L. – Mean Sea Level

☐ SPLIT SPOON SAMPLE
☐ SHELBY TUBE SAMPLE
☐ GRAB SAMPLE
EST. WATER TABLE

Date	09/12/94	ESTDATE	Establishing Company	ESCI	ESCCODE			
Northing	1133028.15 ft.	NCOORD	Drilling Company	Hunt	DRLCODE	Air Force Installation	ELSWH	AFIID
Easting	1156848.79 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP	Location Identification	**MW-25**	LOCID
Borehole Total Depth	23.00 ft.	DEPTH	Construction Method	HS	CMCCODE			



Lithology

USCS	Description	STRATORDER
ASTMCODE	SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –*Initials*	
NACM	ASPHALT –SP	
NACM	FILL –SP	
CL	CLAY, 10YR4/4, dark yellowish brn, little silt, trace of very fine-grained sand, little gravel at 3.21', some reddish orange mottling. @5'SAA–little white marl. –SP	
MLCL	CLAY, 10YR4/4, dark yellowish brn, some fine-grained to very f-grained sand, and silt, trace of fine gravel, Fe-leached fractures. –SP	
GC	GRAVEL AND CLAY, 10YR4/4, dark yellowish brn, some fine-grained sand and silt, poorly, graded, gravel consists of cobble sized shale,chert,quartzite,chlorite shist, and sandstone. –SP	
ML	CLAY AND FINE SAND, 10YR6/2, light	
GC	GRAVEL AND CLAY, SAA – saturated at 16'. brownish gray, some very fine-grained –SP sand and silt, trace of orgainc material. –SP	
CH	CLAY SHALE,10YR3/1, very dark gray, some fissility, not lithified @20' SAA–very small lenses of fine-grained sand, mottling and discoloration, evident of weathering. –SP	

Remarks

Depth *Borehole Diameter* *Drilling Problems* *Weather*	*Time* *Equipment* *Water Level* *–Initials*
Borehole diameter = 7"	

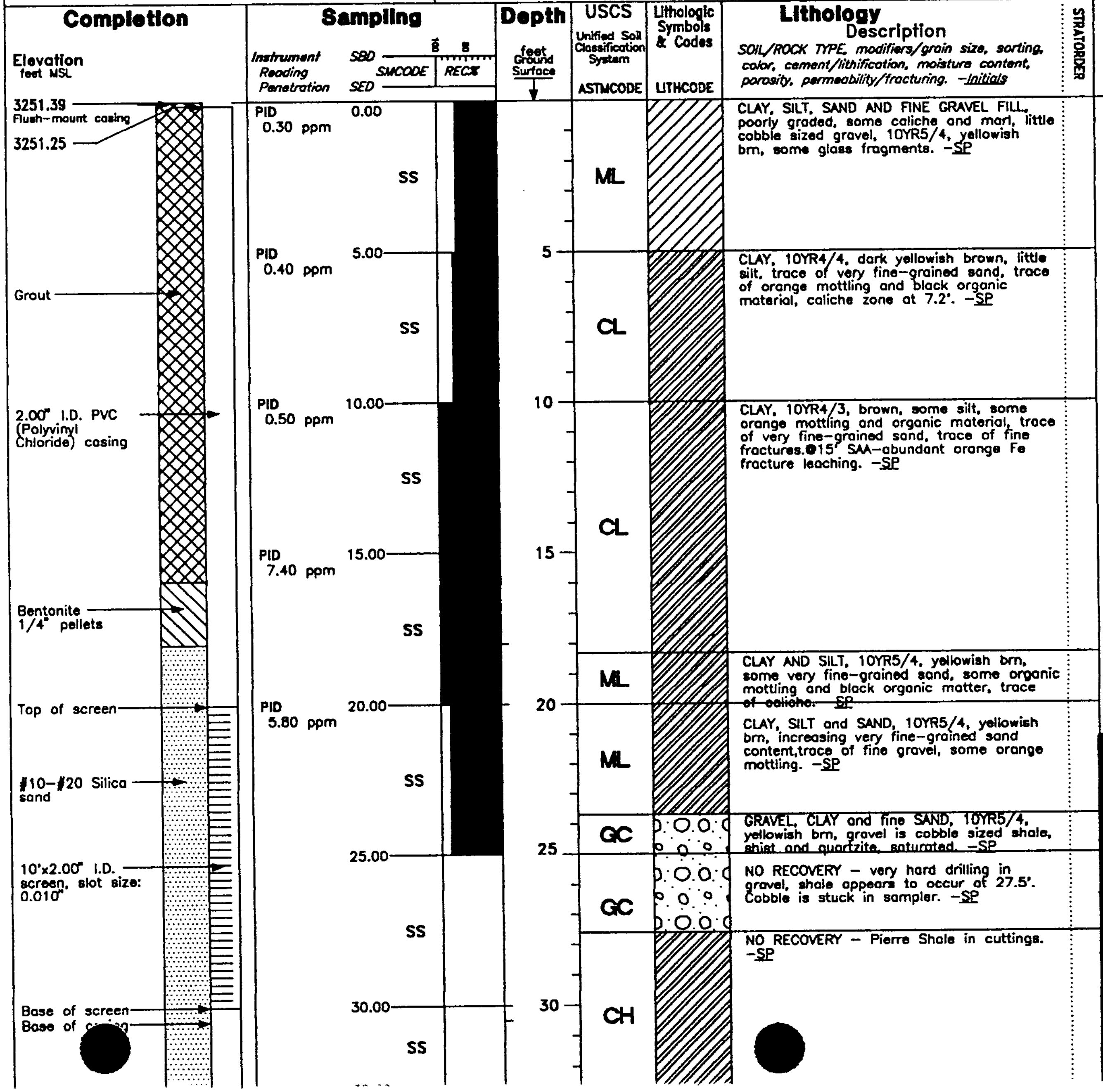
FIGURE D.1

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Date	09/13/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH AFID
Northing	1133337.76 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	MW-26 LOCID
Easting	1156975.65 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP		
Borehole Total Depth	32.70 ft.	DEPTH	Construction Method	HS	CMCCODE		



Completion
Elevation feet MSL
3251.39 Flush-mount casing
3251.25
Grout
2.00" I.D. PVC (Polyvinyl Chloride) casing
Bentonite 1/4" pellets
Top of screen
#10–#20 Silica sand
10'x2.00" I.D. screen, slot size: 0.010"
Base of screen
Base of [illegible]
Sampling
Instrument Reading Penetration
SBD SMCODE SED
18 8 RECX
Depth feet Ground Surface
USCS Unified Soil Classification System ASTMCODE
Lithologic Symbols & Codes LITHCODE
STRATORDER

Instrument Reading	SBD	SMCODE
PID 0.30 ppm	0.00	SS
PID 0.40 ppm	5.00	SS
PID 0.50 ppm	10.00	SS
PID 7.40 ppm	15.00	SS
PID 5.80 ppm	20.00	SS
	25.00	SS
	30.00	SS

USCS	Lithology Description SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials
ML	CLAY, SILT, SAND AND FINE GRAVEL FILL, poorly graded, some caliche and marl, little cobble sized gravel, 10YR5/4, yellowish brn, some glass fragments. –SP
CL	CLAY, 10YR4/4, dark yellowish brown, little silt, trace of very fine-grained sand, trace of orange mottling and black organic material, caliche zone at 7.2'. –SP
CL	CLAY, 10YR4/3, brown, some silt, some orange mottling and organic material, trace of very fine-grained sand, trace of fine fractures.@15' SAA–abundant orange Fe fracture leaching. –SP
ML	CLAY AND SILT, 10YR5/4, yellowish brn, some very fine-grained sand, some organic mottling and black organic matter, ~~trace of caliche.~~ SP
ML	CLAY, SILT and SAND, 10YR5/4, yellowish brn, increasing very fine-grained sand content,trace of fine gravel, some orange mottling. –SP
GC	GRAVEL, CLAY and fine SAND, 10YR5/4, yellowish brn, gravel is cobble sized shale, shist and quartzite, saturated. –SP
GC	NO RECOVERY – very hard drilling in gravel, shale appears to occur at 27.5'. Cobble is stuck in sampler. –SP
CH	NO RECOVERY – Pierre Shale in cuttings. –SP

Remarks

Depth *Time*
Borehole Diameter *Equipment*
Drilling Problems *Water Level*
Weather *–Initials*

Borehole diameter = 7"

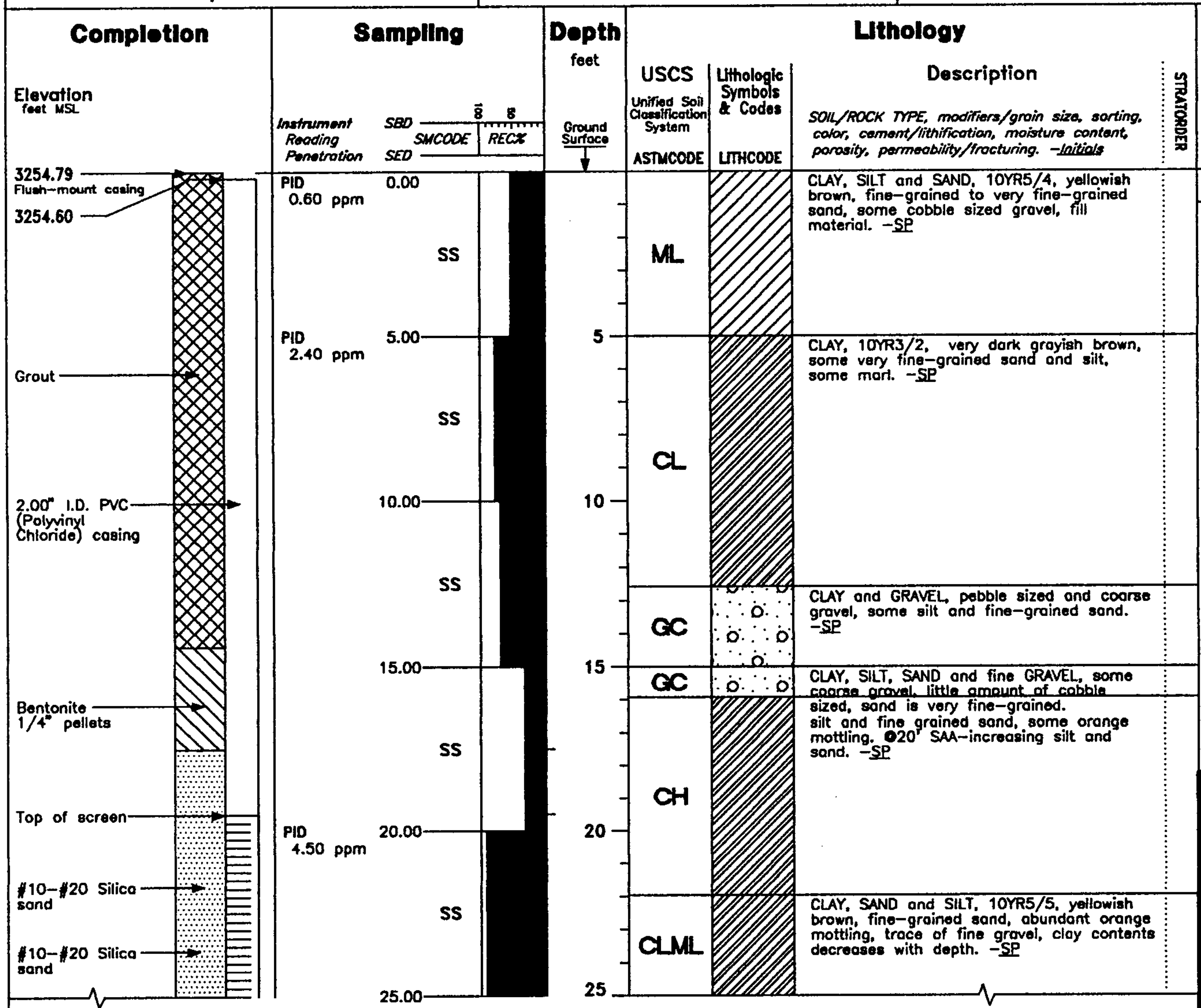
FIGURE D.2

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING S[illegible]CE, INC.
Denver, Colorado

Date	09/14/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFIID
Northing	1133625.05 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**MW-27**	LOCID
Easting	1157004.29 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	35.00 ft.	DEPTH	Construction Method	HS	CMCCODE			



Description

SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. -Initials

USCS	Description
ML	CLAY, SILT and SAND, 10YR5/4, yellowish brown, fine-grained to very fine-grained sand, some cobble sized gravel, fill material. -SP
CL	CLAY, 10YR3/2, very dark grayish brown, some very fine-grained sand and silt, some marl. -SP
GC	CLAY and GRAVEL, pebble sized and coarse gravel, some silt and fine-grained sand. -SP
GC	CLAY, SILT, SAND and fine GRAVEL, some coarse gravel, little amount of cobble sized, sand is very fine-grained.
CH	silt and fine grained sand, some orange mottling. @20' SAA-increasing silt and sand. -SP
CLML	CLAY, SAND and SILT, 10YR5/5, yellowish brown, fine-grained sand, abundant orange mottling, trace of fine gravel, clay contents decreases with depth. -SP

Remarks

Depth
Borehole Diameter
Drilling Problems
Weather
Time
Equipment
Water Level
-Initials

Borehole diameter = 7"

FIGURE D.3

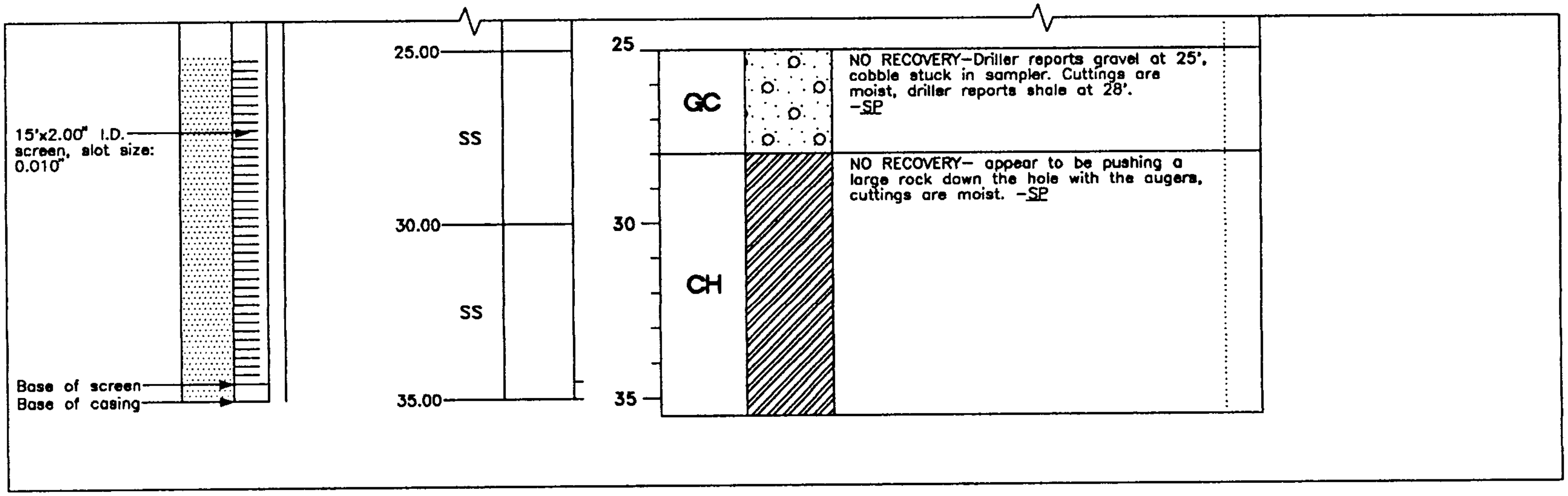
GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Date	09/14/94	ESTDATE	Establishing Company	ESCI	ESCCODE			
Northing	1133625.05 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Air Force Installation	ELSWH	AFIID
Easting	1157004.29 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	35.00 ft.	DEPTH	Construction Method	HS	CMCCODE	Location Identification	**MW-27**	LOCID

Completion	**Sampling**	**Depth**	**Lithology**				**Remarks**
Elevation feet MSL	Instrument Reading Penetration SBD SMCODE SED 100 0 RECX	feet Ground Surface	USCS Unified Soil Classification System ASTMCODE	Lithologic Symbols & Codes LITHCODE	Description *SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials*	STRATORDER	*Depth* *Borehole Diameter* *Drilling Problems* *Weather* *Time* *Equipment* *Water Level* *–Initials*



NO RECOVERY–Driller reports gravel at 25', cobble stuck in sampler. Cuttings are moist, driller reports shale at 28'. –SP

NO RECOVERY– appear to be pushing a large rock down the hole with the augers, cuttings are moist. –SP

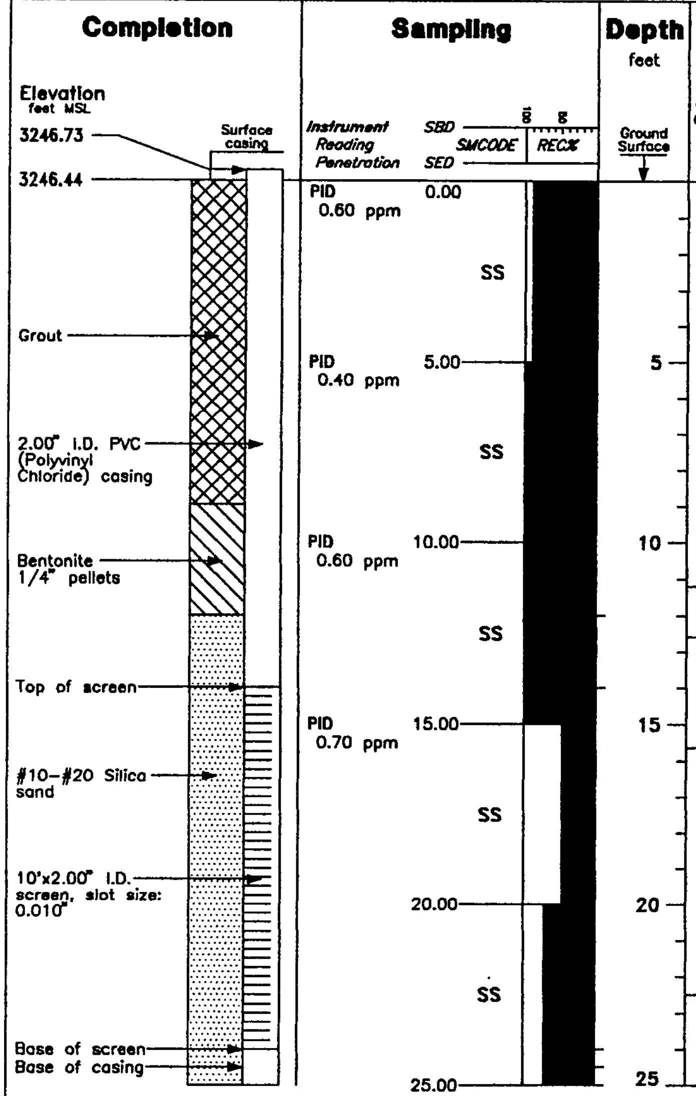
FIGURE D.3
(CONTINUED)

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING S[illegible]NCE, INC.

Date	09/14/94	ESTDATE	Establishing Company	ESCI	ESCCODE			
Northing	1133152.89 ft.	NCOORD	Drilling Company	HUNT	DRLCODE			
Easting	1156679.69 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP	Air Force Installation	ELSWH	AFIID
Borehole Total Depth	25.00 ft.	DEPTH	Construction Method	HS	CMCCODE	Location Identification	**MW-28**	LOCID



Lithology

USCS Unified Soil Classification System ASTMCODE	Lithologic Symbols & Codes LITHCODE	Description SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials	STRATORDER
CL	▨	CLAY, 10YR5/4, yellowish brown, some silt and very fine grained sand, little amount of orgaonic material, leached CaCO3 in fractures @5' SAA–orange mottling along fracture planes. –SP	
ML	▨	CLAY, SILT and SAND, 10YR5/4, yellowish brown, sand is fine-grained. –SP	
SC		SAND, 10YR6/4, light yellowish brown, fine to very fine-grained, some silt and clay @15' SAA–severe orange mottling. –SP	
GC		CLAY, GRAVEL and SAND, fine-grained sand, some silt, pebble and cobble sized gravel consisting of shale, quartzite and schists, saturated at 19'. –SP	
CH	▨	CLAY SHALE, 2.5YR3/1, very dark gray, very fat clay, fractured and leaching along fracute planes – SP	

Remarks

Depth
Borehole Diameter
Drilling Problems
Weather

Time
Equipment
Water Level
–Initials

FIGURE D.4

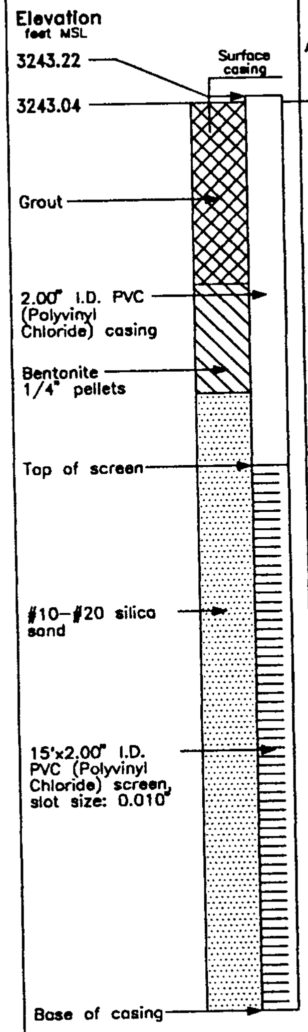
GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Date	09/15/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFIID
Northing	1133032.47 ft.	NCOORD	Drilling Company	HUND	DRLCODE	Location Identification	**MW-29**	LOCID
Easting	1156682.70 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	25.00 ft.	DEPTH	Construction Method	HS	CMCCODE			

Completion



Sampling

Instrument Reading Penetration	SBD / SED	SMCODE
PID 1.10 ppm	0.00	SS
PID 0.60 ppm	5.00	SS
PID 0.90 ppm	10.00	SS
PID >300.00 ppm	15.00	SS
PID 24.90 ppm	20.00	SS
	25.00	

RECX: 0 – 100

Depth

feet

Ground Surface

Lithology

USCS Unified Soil Classification System ASTMCODE	Lithologic Symbols & Codes LITHCODE	Description: SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials	STRATORDER
ML	▨	CLAY, SILT and SAND, 10YR5/4, yellowish brown, very fine-grained sand, abundant plant material. –SP	
CL	▨	CLAY, 10YR4/4, dark yellowish brown, some silt, trace of very fine-grained sand, little orange mottling, hard. –SP	
CH	▨	CLAY, 10YR4/3, brown, abundant orange mottling, abundant caliche and marl, trace of root material, some dark organic matter or manganese staining @10' SAA– trace of fine gravel. –SP	
GC	○	CLAY and GRAVEL comformable increase in gravel percentage with above, pebbles to coarse gravel. –SP	
GC	○	SILT, GRAVEL, SAND and CLAY, pebble to cobble sized, mostly medium gravel, very fine-grained sand. –SP	
GC	○	GRAVEL, CLAY and SILT, very poorly sorted, wet to saturated, water on spoon to 18'. –SP	
CH	▨	CAVINGS, saturated to 21.68 then CLAY SHALE, 5YR3/1, very dark gray, some fissility, weathered, little fracturing. –SP	

Remarks

Depth Borehole Diameter Drilling Problems Weather	Time Equipment Water Level –Initials
Borehole diameter = 7"	

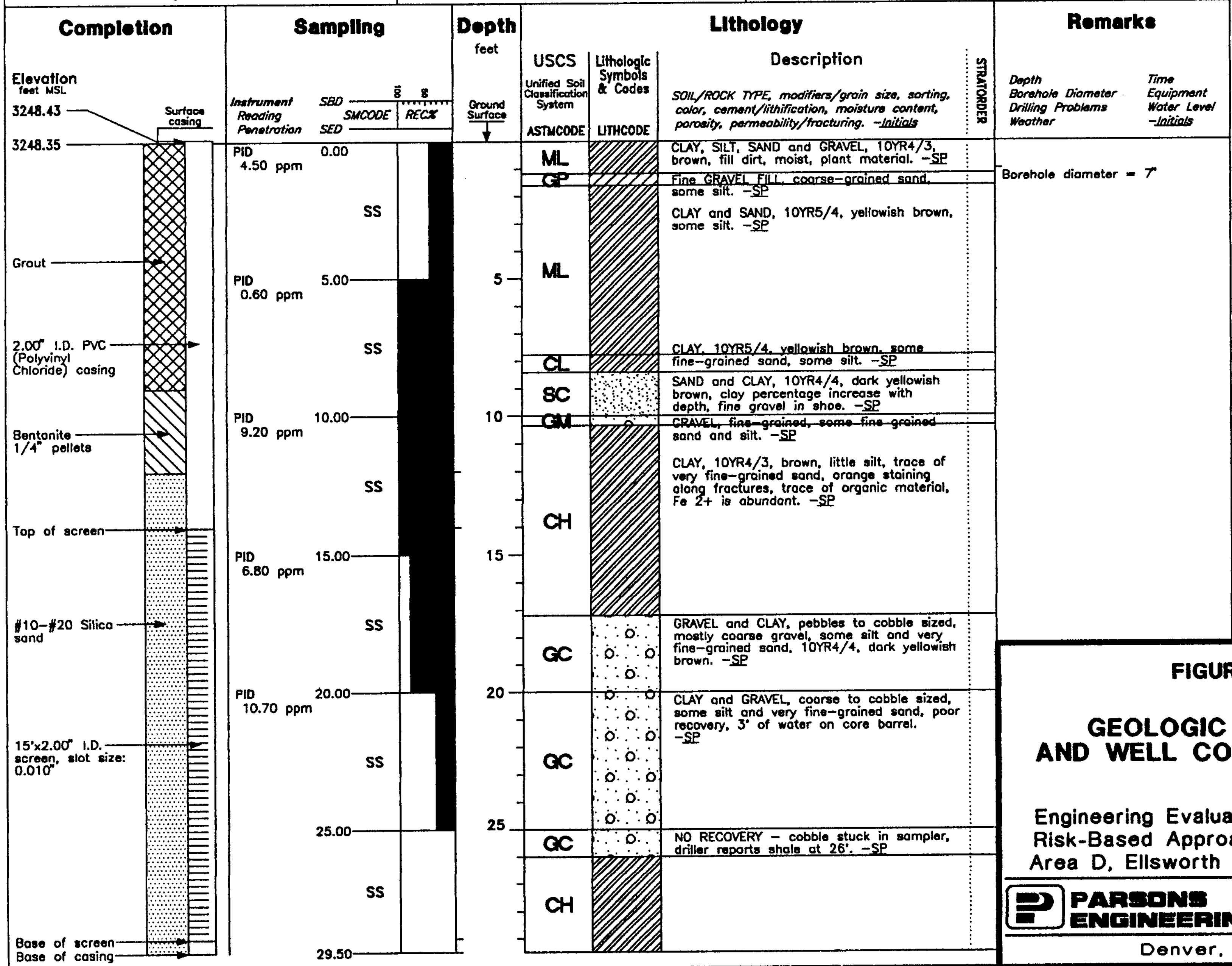
FIGURE D.5

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SC NCE, INC.
Denver, Colorado

Date	09/15/94	ESTDATE	Establishing Company	ESCI	ESCCODE		
Northing	1133225.67 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Air Force Installation	ELSWH AFIID
Easting	1156559.52 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP	Location Identification	**MW-30** LOCID
Borehole Total Depth	29.50 ft.	DEPTH	Construction Method	HS	CMCCODE		



USCS	Description
ML	CLAY, SILT, SAND and GRAVEL, 10YR4/3, brown, fill dirt, moist, plant material. –SP
GP	Fine GRAVEL FILL, coarse-grained sand, some silt. –SP
ML	CLAY and SAND, 10YR5/4, yellowish brown, some silt. –SP
CL	CLAY, 10YR5/4, yellowish brown, some fine-grained sand, some silt. –SP
SC	SAND and CLAY, 10YR4/4, dark yellowish brown, clay percentage increase with depth, fine gravel in shoe. –SP
GM	GRAVEL, fine-grained, some fine-grained sand and silt. –SP
CH	CLAY, 10YR4/3, brown, little silt, trace of very fine-grained sand, orange staining along fractures, trace of organic material, Fe 2+ is abundant. –SP
GC	GRAVEL and CLAY, pebbles to cobble sized, mostly coarse gravel, some silt and very fine-grained sand, 10YR4/4, dark yellowish brown. –SP
GC	CLAY and GRAVEL, coarse to cobble sized, some silt and very fine-grained sand, poor recovery, 3' of water on core barrel. –SP
GC	NO RECOVERY – cobble stuck in sampler, driller reports shale at 26'. –SP
CH	

Borehole diameter = 7"

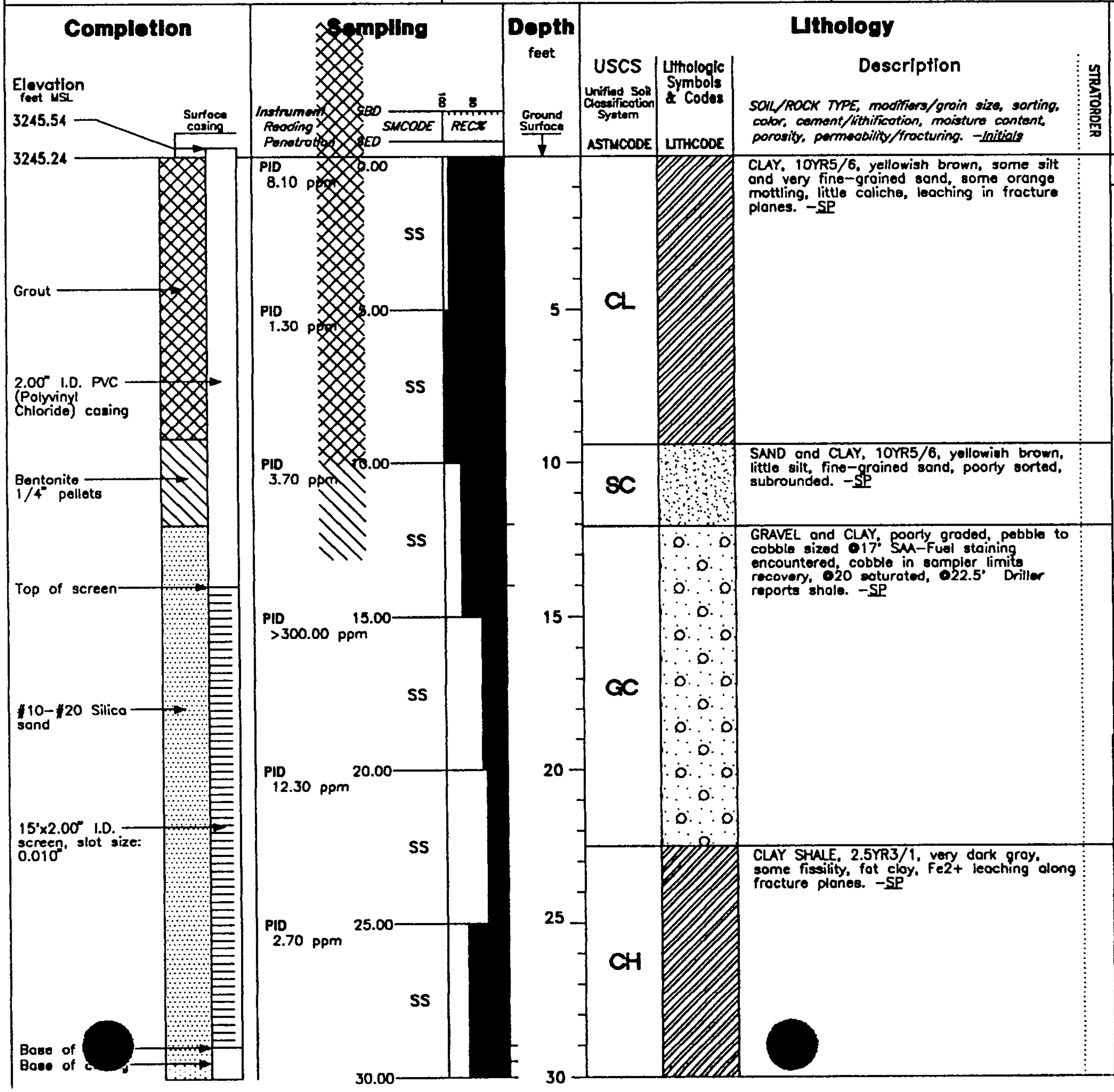
FIGURE D.6

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Date	09/16/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFIID
Northing	1133103.97 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**MW-31**	LOCID
Easting	1156553.16 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	30.00 ft.	DEPTH	Construction Method	HS	CMCCODE			



Description

SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials

USCS	Description
CL	CLAY, 10YR5/6, yellowish brown, some silt and very fine-grained sand, some orange mottling, little caliche, leaching in fracture planes. –SP
SC	SAND and CLAY, 10YR5/6, yellowish brown, little silt, fine-grained sand, poorly sorted, subrounded. –SP
GC	GRAVEL and CLAY, poorly graded, pebble to cobble sized @17' SAA–Fuel staining encountered, cobble in sampler limits recovery, @20 saturated, @22.5' Driller reports shale. –SP
CH	CLAY SHALE, 2.5YR3/1, very dark gray, some fissility, fat clay, Fe2+ leaching along fracture planes. –SP

Remarks

Depth *Borehole Diameter* *Drilling Problems* *Weather*	*Time* *Equipment* *Water Level* *–Initials*

Borehole diameter = 7"

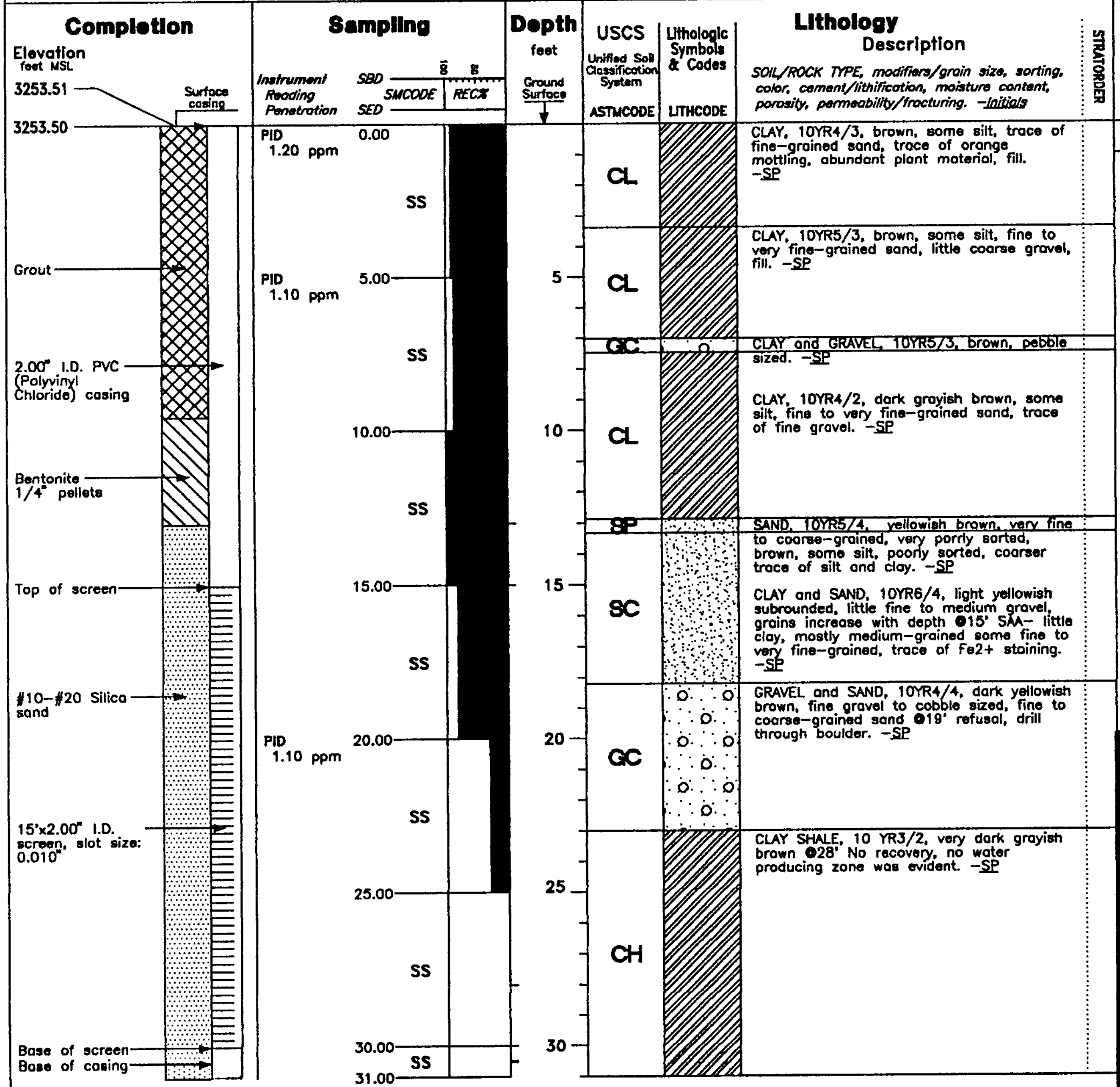
FIGURE D.7

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SC ICE, INC.
Denver, Colorado

Date	09/16/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFIID
Northing	1132931.04 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**MW-32**	LOCID
Easting	1156114.25 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	31.00 ft.	DEPTH	Construction Method	HS	CMCCODE			



USCS Unified Soil Classification System ASTMCODE	Lithology Description *SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials*	STRATORDER	Remarks *Depth Borehole Diameter Drilling Problems Weather Time Equipment Water Level –Initials*
CL	CLAY, 10YR4/3, brown, some silt, trace of fine-grained sand, trace of orange mottling, abundant plant material, fill. –SP		Borehole diameter = 7"
CL	CLAY, 10YR5/3, brown, some silt, fine to very fine-grained sand, little coarse gravel, fill. –SP		
GC	CLAY and GRAVEL, 10YR5/3, brown, pebble sized. –SP		
CL	CLAY, 10YR4/2, dark grayish brown, some silt, fine to very fine-grained sand, trace of fine gravel. –SP		
SP	SAND, 10YR5/4, yellowish brown, very fine to coarse-grained, very porrly sorted, brown, some silt, poorly sorted, coarser trace of silt and clay. –SP		
SC	CLAY and SAND, 10YR6/4, light yellowish subrounded, little fine to medium gravel, grains increase with depth @15' SAA– little clay, mostly medium-grained some fine to very fine-grained, trace of Fe2+ staining. –SP		
GC	GRAVEL and SAND, 10YR4/4, dark yellowish brown, fine gravel to cobble sized, fine to coarse-grained sand @19' refusal, drill through boulder. –SP		
CH	CLAY SHALE, 10 YR3/2, very dark grayish brown @28' No recovery, no water producing zone was evident. –SP		

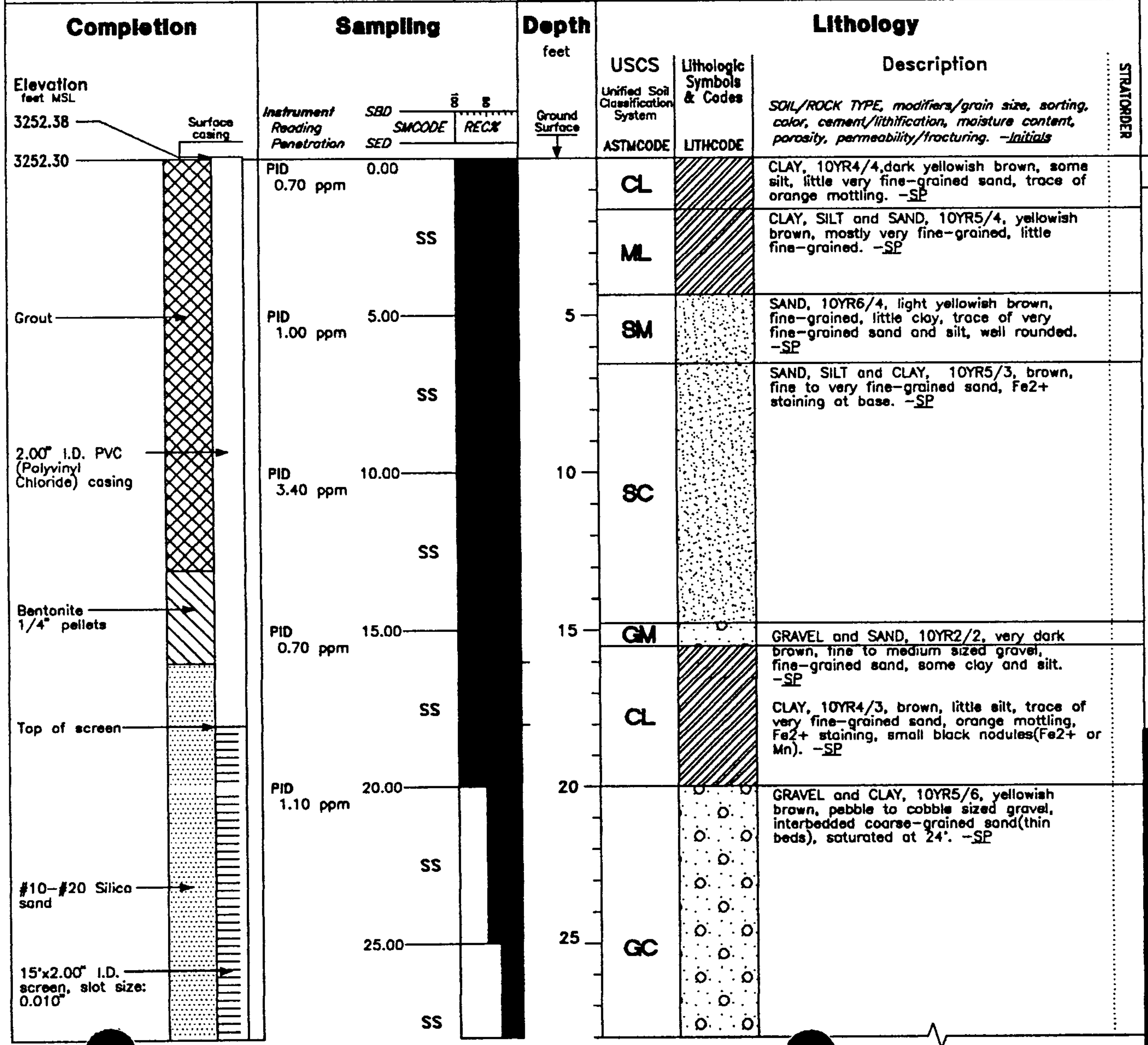
FIGURE D.8

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Date	09/19/94 ESTDATE	Establishing Company	ESCI ESCCODE	Air Force Installation	ELSWH AFIID
Northing	1133394.99 ft. NCOORD	Drilling Company	HUNT DRLCODE	Location Identification	**MW-33** LOCID
Easting	1156440.29 ft. ECOORD	Drill Rig Type	HSA DRLEQP		
Borehole Total Depth	35.00 ft. DEPTH	Construction Method	HS CMCCODE		



Sampling

Instrument Reading Penetration	SBD / SMCODE / SED
PID 0.70 ppm	0.00 SS
PID 1.00 ppm	5.00 SS
PID 3.40 ppm	10.00 SS
PID 0.70 ppm	15.00 SS
PID 1.10 ppm	20.00 SS
	25.00 SS

Lithology

USCS Unified Soil Classification System ASTMCODE	Description SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. -Initials
CL	CLAY, 10YR4/4, dark yellowish brown, some silt, little very fine-grained sand, trace of orange mottling. -SP
ML	CLAY, SILT and SAND, 10YR5/4, yellowish brown, mostly very fine-grained, little fine-grained. -SP
SM	SAND, 10YR6/4, light yellowish brown, fine-grained, little clay, trace of very fine-grained sand and silt, well rounded. -SP
SC	SAND, SILT and CLAY, 10YR5/3, brown, fine to very fine-grained sand, Fe2+ staining at base. -SP
GM	GRAVEL and SAND, 10YR2/2, very dark brown, fine to medium sized gravel, fine-grained sand, some clay and silt. -SP
CL	CLAY, 10YR4/3, brown, little silt, trace of very fine-grained sand, orange mottling, Fe2+ staining, small black nodules(Fe2+ or Mn). -SP
GC	GRAVEL and CLAY, 10YR5/6, yellowish brown, pebble to cobble sized gravel, interbedded coarse-grained sand(thin beds), saturated at 24'. -SP

Remarks

Depth, Borehole Diameter, Drilling Problems, Weather; Time, Equipment, Water Level -Initials

Borehole diameter = 7"

FIGURE D.9

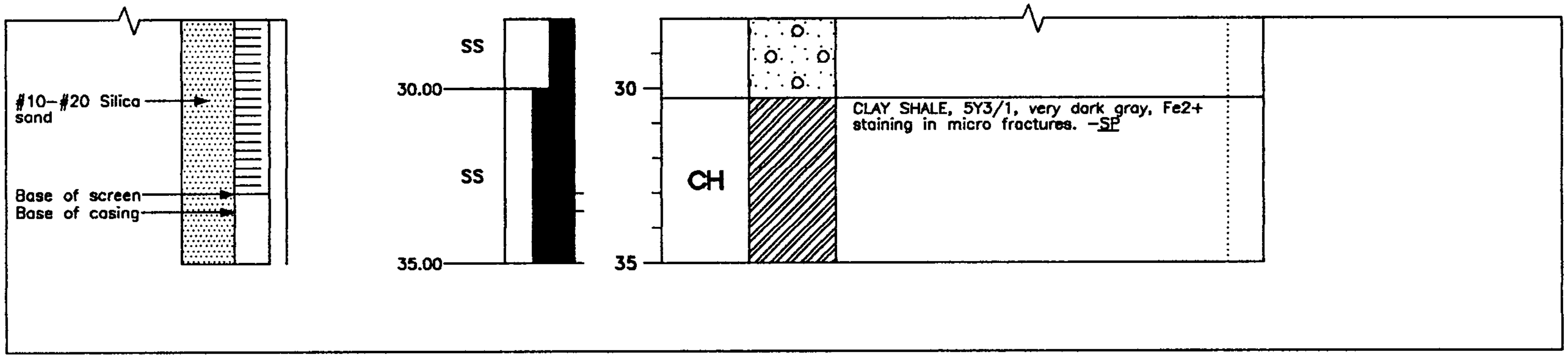
GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SC NCE, INC.
Denver, Colorado

Date	09/19/94	ESTDATE	Establishing Company	ESCI	ESCCODE			
Northing	1133394.99 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Air Force Installation	ELSWH	AFIID
Easting	1156440.29 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP	Location Identification	**MW-33**	LOCID
Borehole Total Depth	35.00 ft.	DEPTH	Construction Method	HS	CMCCODE			

Completion	**Sampling**	**Depth**	**Lithology**				**Remarks**
		feet	USCS	Lithologic Symbols & Codes	Description	STRATORDER	
	Instrument Reading Penetration SBD SMCODE SED 100 50 RECX	Ground Surface	Unified Soil Classification System ASTMCODE	LITHCODE	*SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials*		*Depth Time* *Borehole Diameter Equipment* *Drilling Problems Water Level* *Weather –Initials*



CLAY SHALE, 5Y3/1, very dark gray, Fe2+ staining in micro fractures. –SP

FIGURE D.9
(CONTINUED)

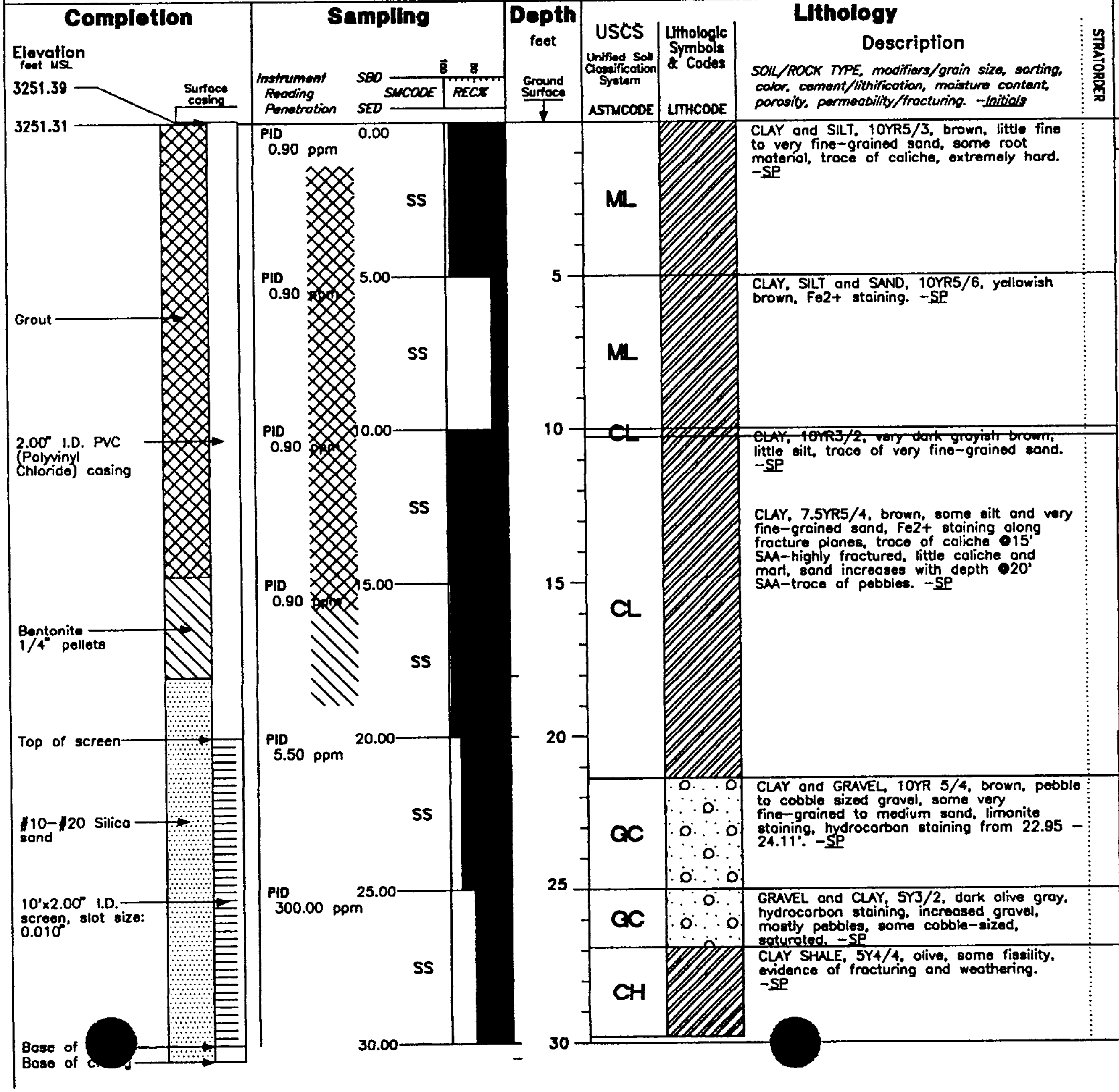
GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.

Denver, Colorado

Date	09/20/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFID
Northing	1133157.34 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**MW-34**	LOCID
Easting	1156438.61 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	30.00 ft.	DEPTH	Construction Method	HS	CMCCODE			



Lithology

Description

SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials

USCS	Description
ML	CLAY and SILT, 10YR5/3, brown, little fine to very fine-grained sand, some root material, trace of caliche, extremely hard. –SP
ML	CLAY, SILT and SAND, 10YR5/6, yellowish brown, Fe2+ staining. –SP
CL	CLAY, 10YR3/2, very dark grayish brown, little silt, trace of very fine-grained sand. –SP
CL	CLAY, 7.5YR5/4, brown, some silt and very fine-grained sand, Fe2+ staining along fracture planes, trace of caliche @15' SAA–highly fractured, little caliche and marl, sand increases with depth @20' SAA–trace of pebbles. –SP
GC	CLAY and GRAVEL, 10YR 5/4, brown, pebble to cobble sized gravel, some very fine-grained to medium sand, limonite staining, hydrocarbon staining from 22.95 – 24.11'. –SP
GC	GRAVEL and CLAY, 5Y3/2, dark olive gray, hydrocarbon staining, increased gravel, mostly pebbles, some cobble-sized, saturated. –SP
CH	CLAY SHALE, 5Y4/4, olive, some fissility, evidence of fracturing and weathering. –SP

Remarks

Depth
Borehole Diameter
Drilling Problems
Weather
Time
Equipment
Water Level
–Initials

Borehole diameter = 9.5"

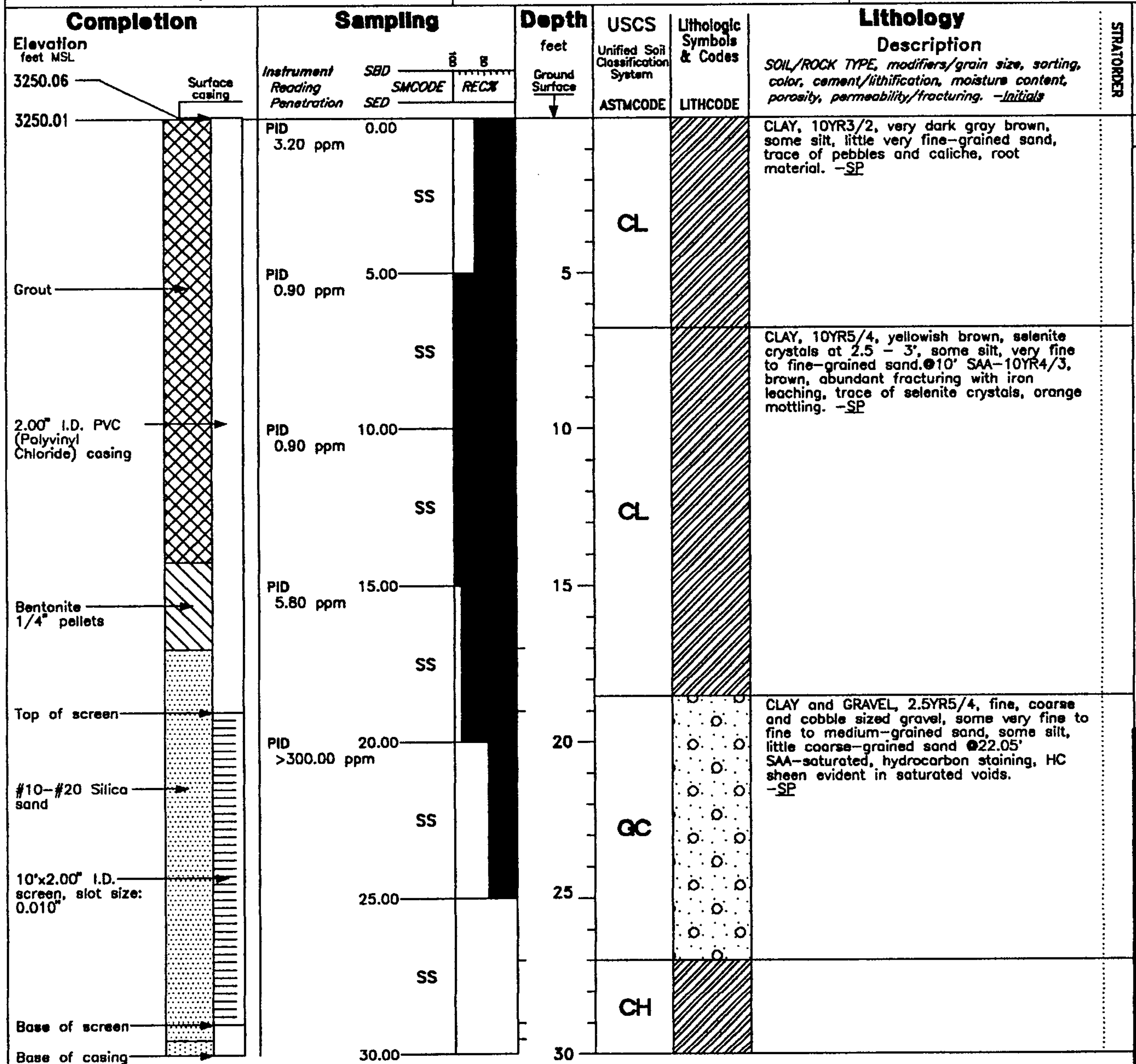
FIGURE D.10

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING S[illegible]NCE, INC.
Denver, Colorado

Date	09/20/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH AFIID
Northing	1133092.71 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**MW-35** LOCID
Easting	1156446.91 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP		
Borehole Total Depth	30.00 ft.	DEPTH	Construction Method	HS	CMCCODE		



Lithology

Description

SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials

CLAY, 10YR3/2, very dark gray brown, some silt, little very fine-grained sand, trace of pebbles and caliche, root material. –SP

CLAY, 10YR5/4, yellowish brown, selenite crystals at 2.5 – 3', some silt, very fine to fine-grained sand.@10' SAA–10YR4/3, brown, abundant fracturing with iron leaching, trace of selenite crystals, orange mottling. –SP

CLAY and GRAVEL, 2.5YR5/4, fine, coarse and cobble sized gravel, some very fine to fine to medium-grained sand, some silt, little coarse-grained sand @22.05' SAA–saturated, hydrocarbon staining, HC sheen evident in saturated voids. –SP

Remarks

Depth, Borehole Diameter, Drilling Problems, Weather, Time, Equipment, Water Level –Initials

Borehole diameter = 9.5"

FIGURE D.11

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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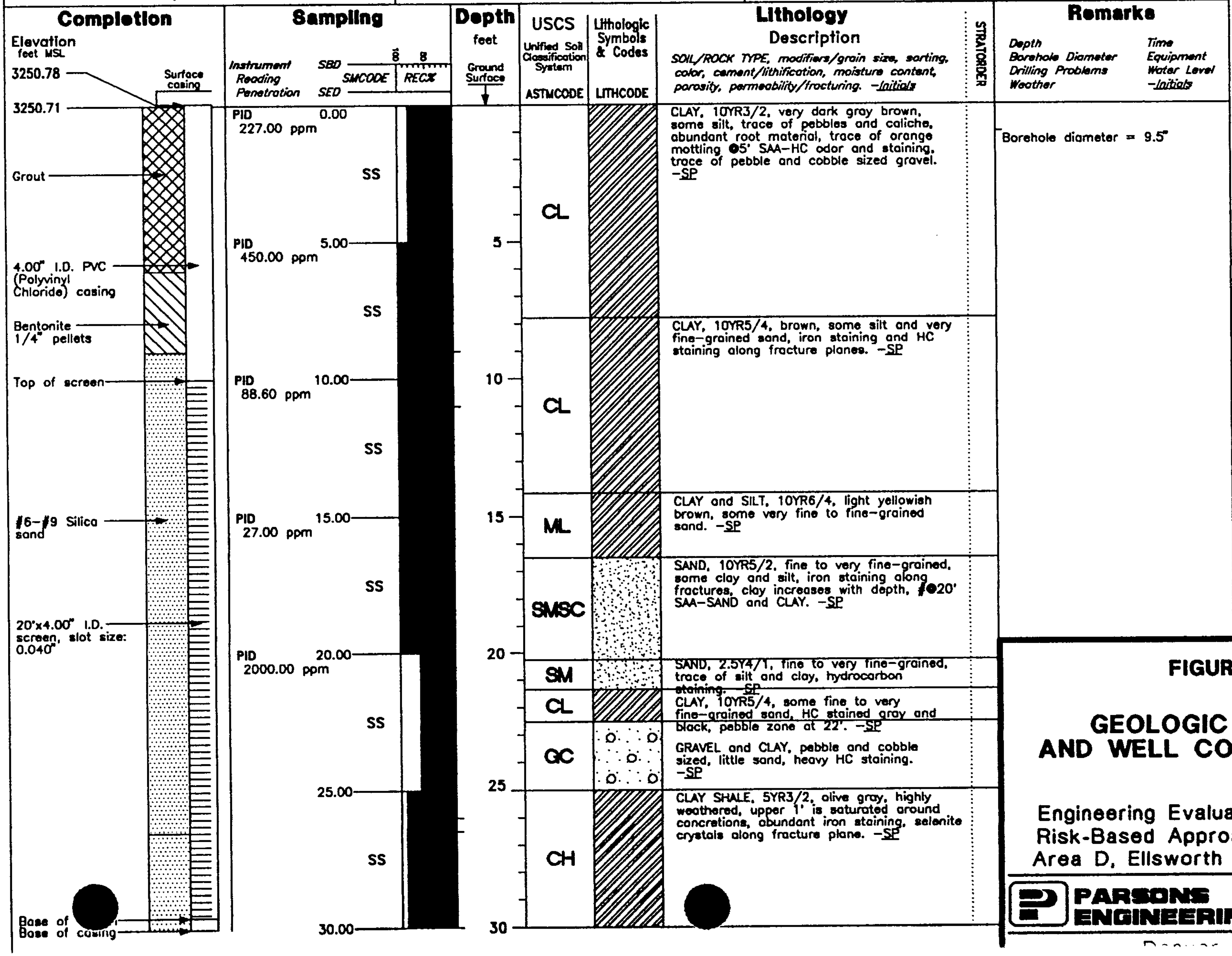
Date	09/21/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFIID
Northing	1133105.64 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**MW-36**	LOCID
Easting	1156404.67 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	30.00 ft.	DEPTH	Construction Method	HS	CMCCODE			



USCS	Lithology Description (SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials)
CL	CLAY, 10YR3/2, very dark gray brown, some silt, trace of pebbles and caliche, abundant root material, trace of orange mottling @5' SAA–HC odor and staining, trace of pebble and cobble sized gravel. –SP
CL	CLAY, 10YR5/4, brown, some silt and very fine–grained sand, iron staining and HC staining along fracture planes. –SP
ML	CLAY and SILT, 10YR6/4, light yellowish brown, some very fine to fine–grained sand. –SP
SMSC	SAND, 10YR5/2, fine to very fine–grained, some clay and silt, iron staining along fractures, clay increases with depth, #@20' SAA–SAND and CLAY. –SP
SM	SAND, 2.5Y4/1, fine to very fine–grained, trace of silt and clay, hydrocarbon staining. –SP
CL	CLAY, 10YR5/4, some fine to very fine–grained sand, HC stained gray and black, pebble zone at 22'. –SP
GC	GRAVEL and CLAY, pebble and cobble sized, little sand, heavy HC staining. –SP
CH	CLAY SHALE, 5YR3/2, olive gray, highly weathered, upper 1' is saturated around concretions, abundant iron staining, selenite crystals along fracture plane. –SP

Remarks

Depth *Borehole Diameter* *Drilling Problems* *Weather* *Time* *Equipment* *Water Level* *–Initials*

Borehole diameter = 9.5"

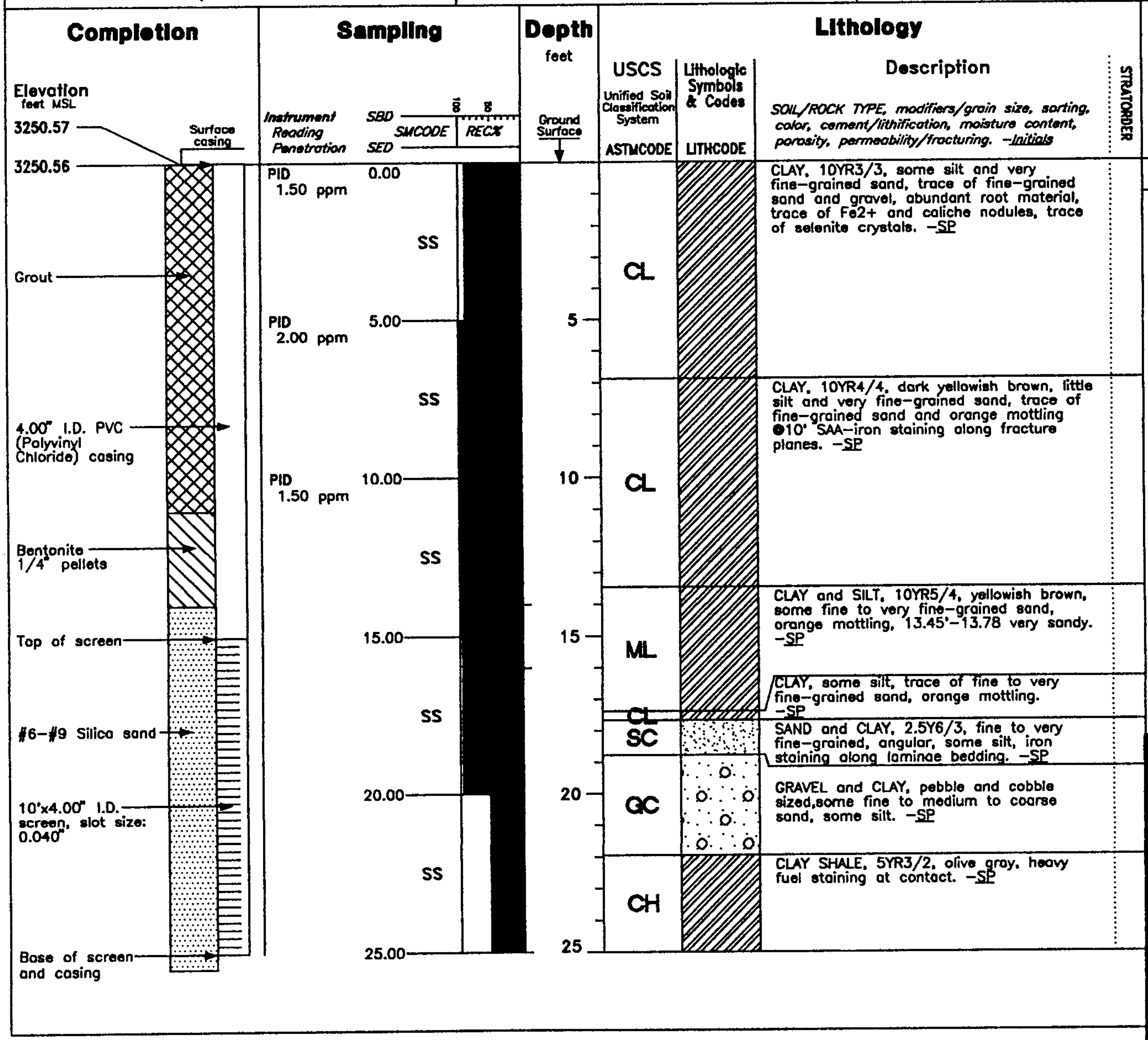
FIGURE D.12

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Date	09/21/94	ESTDATE	Establishing Company	ESCI	ESCCODE						
Northing	1133069.03 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Air Force Installation	ELSWH	AFIID			
Easting	1156370.13 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP	Location Identification	MW-37	LOCID			
Borehole Total Depth	25.00 ft.	DEPTH	Construction Method	HS	CMCCODE						



Description

SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials

CLAY, 10YR3/3, some silt and very fine–grained sand, trace of fine–grained sand and gravel, abundant root material, trace of Fe2+ and caliche nodules, trace of selenite crystals. –SP

CLAY, 10YR4/4, dark yellowish brown, little silt and very fine–grained sand, trace of fine–grained sand and orange mottling @10' SAA–iron staining along fracture planes. –SP

CLAY and SILT, 10YR5/4, yellowish brown, some fine to very fine–grained sand, orange mottling, 13.45'–13.78 very sandy. –SP

CLAY, some silt, trace of fine to very fine–grained sand, orange mottling. –SP

SAND and CLAY, 2.5Y6/3, fine to very fine–grained, angular, some silt, iron staining along laminae bedding. –SP

GRAVEL and CLAY, pebble and cobble sized, some fine to medium to coarse sand, some silt. –SP

CLAY SHALE, 5YR3/2, olive gray, heavy fuel staining at contact. –SP

Remarks

Depth	*Time*
Borehole Diameter	*Equipment*
Drilling Problems	*Water Level*
Weather	*–Initials*

Borehole diameter = 9.5"

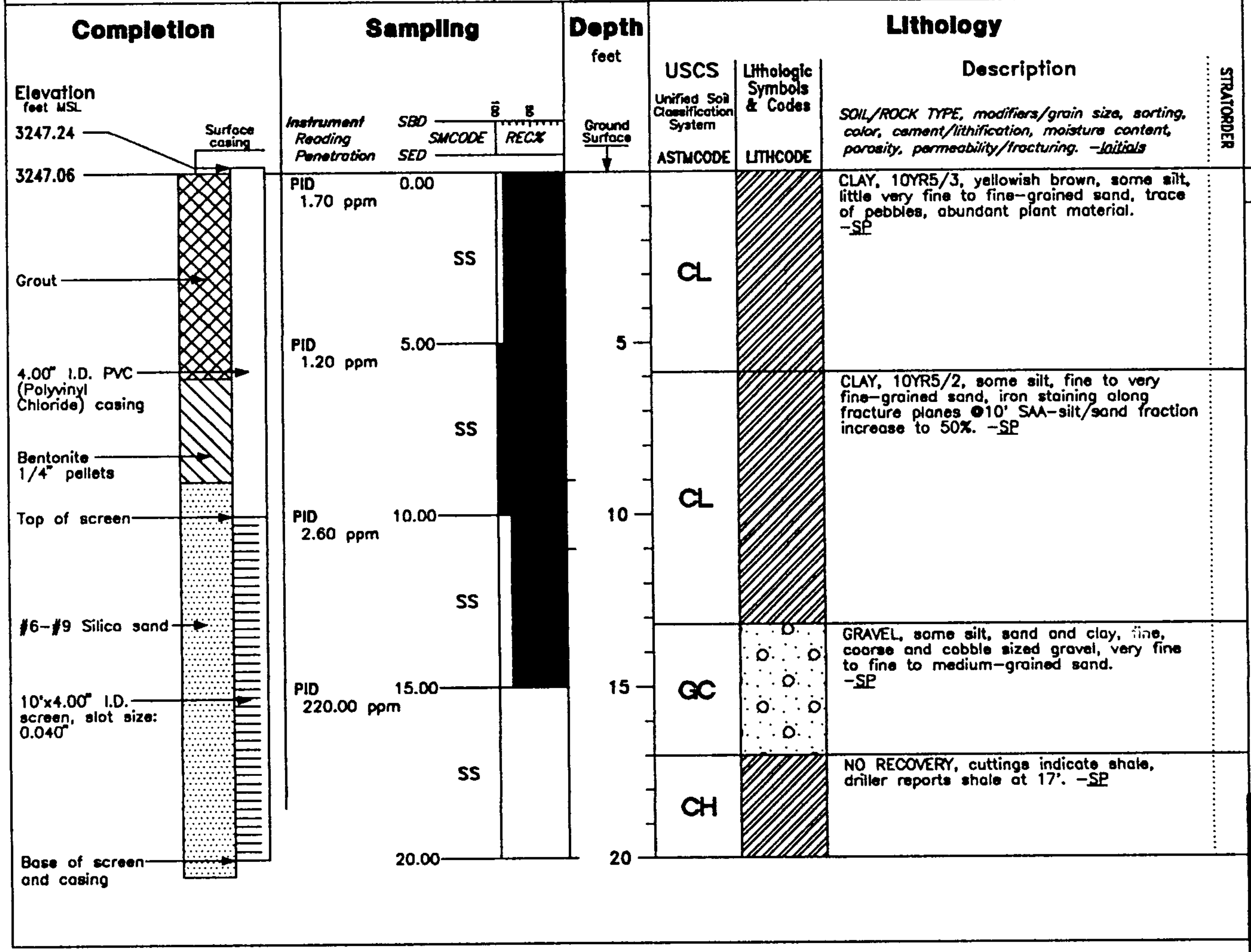
FIGURE D.13

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Date	09/22/94	ESTDATE
Northing	1132961.47 ft.	NCOORD
Easting	1156353.09 ft.	ECOORD
Borehole Total Depth	20.00 ft.	DEPTH
Establishing Company	ESCI	ESCCODE
Drilling Company	HUNT	DRLCODE
Drill Rig Type	HSA	DRLEQP
Construction Method	HS	CMCCODE
Air Force Installation	ELSWH	AFIID
Location Identification	**MW-38**	LOCID



CLAY, 10YR5/3, yellowish brown, some silt, little very fine to fine-grained sand, trace of pebbles, abundant plant material. –SP

CLAY, 10YR5/2, some silt, fine to very fine-grained sand, iron staining along fracture planes @10' SAA-silt/sand fraction increase to 50%. –SP

GRAVEL, some silt, sand and clay, fine, coarse and cobble sized gravel, very fine to fine to medium-grained sand. –SP

NO RECOVERY, cuttings indicate shale, driller reports shale at 17'. –SP

Borehole diameter = 9.5"

FIGURE D.14

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

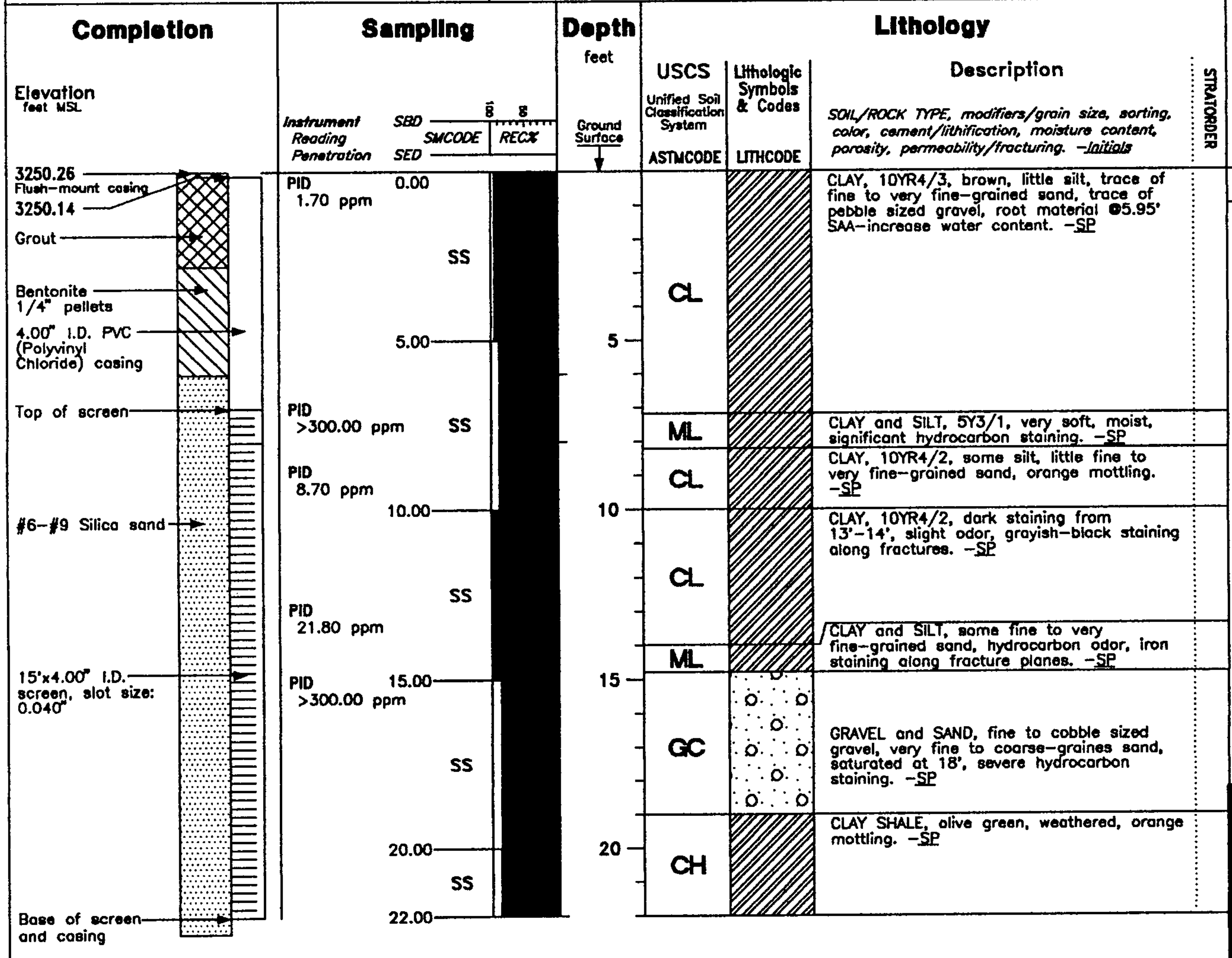
Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS
ENGINEERING S NCE, INC.
Denver, Colorado

Date	09/22/94		ESTDATE
Northing	1132995.23	ft.	NCOORD
Easting	1156299.34	ft.	ECOORD
Borehole Total Depth	22.00	ft.	DEPTH

Establishing Company	ESCI	ESCCODE
Drilling Company	HUNT	DRLCODE
Drill Rig Type	HSA	DRLEQP
Construction Method	HS	CMCCODE

Air Force Installation	ELSWH	AFID
Location Identification	**MW-39**	LOCID



Lithology

Description

SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials

USCS	Description
CL	CLAY, 10YR4/3, brown, little silt, trace of fine to very fine-grained sand, trace of pebble sized gravel, root material @5.95' SAA–increase water content. –SP
ML	CLAY and SILT, 5Y3/1, very soft, moist, significant hydrocarbon staining. –SP
CL	CLAY, 10YR4/2, some silt, little fine to very fine-grained sand, orange mottling. –SP
CL	CLAY, 10YR4/2, dark staining from 13'-14', slight odor, grayish-black staining along fractures. –SP
ML	CLAY and SILT, some fine to very fine-grained sand, hydrocarbon odor, iron staining along fracture planes. –SP
GC	GRAVEL and SAND, fine to cobble sized gravel, very fine to coarse-graines sand, saturated at 18', severe hydrocarbon staining. –SP
CH	CLAY SHALE, olive green, weathered, orange mottling. –SP

Remarks

Depth *Borehole Diameter* *Drilling Problems* *Weather*	*Time* *Equipment* *Water Level* *–Initials*

Borehole diameter = 9.5"

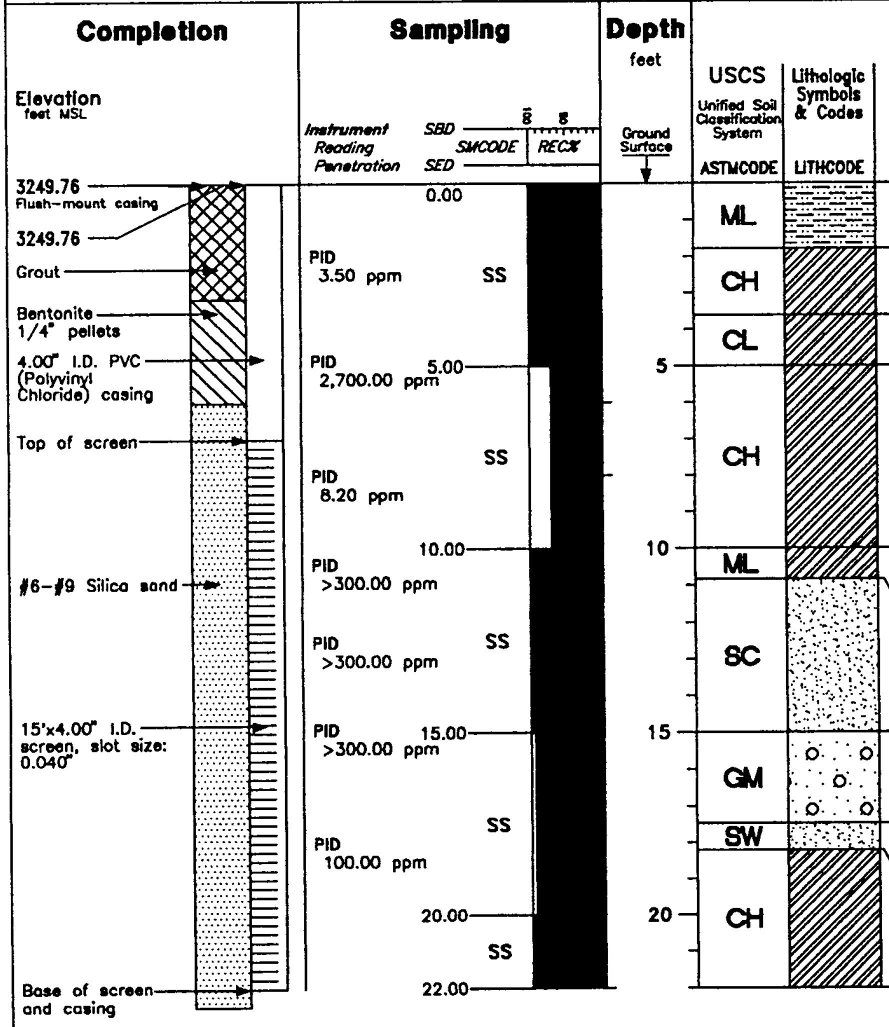
FIGURE D.15

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Date	09/23/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFID
Northing	1132937.18 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**MW-40**	LOCID
Easting	1156248.88 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	22.00 ft.	DEPTH	Construction Method	HS	CMCCODE			



Lithology

USCS Unified Soil Classification System ASTMCODE	Description SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. -Initials	STRATORDER
ML	SILT, CLAY and SAND, 10YR4/2, dry, loose, trace of pebbles. -SP	
CH	CLAY, 2.5Y4/2, trace of silt. -SP	
CL	CLAY, little silt, trace of very fine-grained sand, heavy HC staining, trace of marl. -SP	
CH	CLAY, 2.5Y4/1, trace of silt and very fine-grained sand, hydrocarbon staining, very moist, and soft. -SP	
ML	CLAY and SILT, 2.5Y4/2, trace of very fine-grained sand, hydrocarbon stained. -SP	
SC	SAND, 2.5Y5/2, some clay and silt, very fine to fine-grained, hydrocarbon stained, iron staining along laminae at 4.5'. -SP	
GM	SAND and GRAVEL, very fine to coarse-grained sand, pebble to cobble sized gravel. -SP	
SW	SAND, 2.5Y4/1, medium-grained, well sorted, well rounded, little clay, hydrocarbon staining. -SP	
CH	CLAY SHALE, weathered, iron staining and mottling, 5Y4/1. -SP	

Remarks

Depth Borehole Diameter Drilling Problems Weather	Time Equipment Water Level -Initials
Borehole diameter = 9.5"	

FIGURE D.16

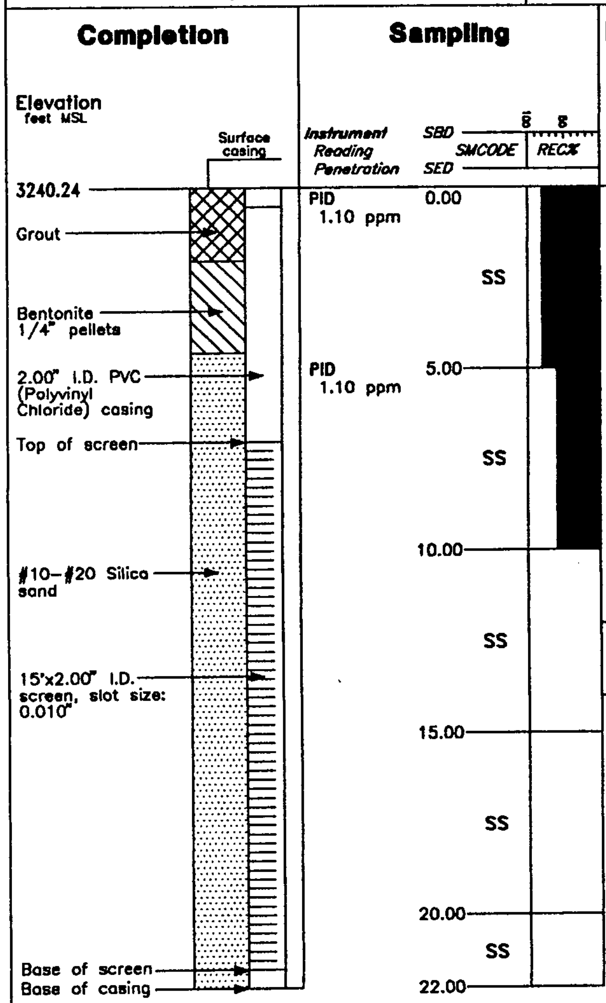
GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING S[illegible]NCE, INC.
Denver, Colorado

Date	09/25/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFIID
Northing	1132912.57 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**MW-41**	LOCID
Easting	1156697.73 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	22.00 ft.	DEPTH	Construction Method	HS	CMCCODE			

Completion



Sampling

Instrument Reading Penetration	SBD / SED	SMCODE
PID 1.10 ppm	0.00 – 5.00	SS
PID 1.10 ppm	5.00 – 10.00	SS
	10.00 – 15.00	SS
	15.00 – 20.00	SS
	20.00 – 22.00	SS

Depth

feet

Ground Surface

5 · 10 · 15 · 20 · 22

Lithology

USCS Unified Soil Classification System ASTMCODE	Description SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –Initials
SC	SAND, SILT and CLAY, 2.5YR6/4, very fine grained and medium-grained, little pebble to cobble-sized gravel, some plant material.
ML	CLAY and SILT, 10YR5/3, yellowish brown, some very fine-grained sand.
CH	CLAY, 10RY4/3, brown, some silt, iron staining and orange mottling, little manganese staining.
GC	GRAVEL and SAND, pebble to cobble-size, fine-grained and very fine grained sand, some clay. Heavy Fe++ staining. CLAY increases with depth. Driller reports gravel at 7' BGL.
GC	NO RECOVERY, cabble stuck in sampler. Driller reports shale at 13' BGL.
CH	NO RECOVERY. Drill indicates shale. No water was encountered during drilling.
CH	
CH	NO RECOVERY. Cuttings inicate damp shale.

Lithologic Symbols & Codes LITHCODE

STRATORDER

Remarks

Depth
Borehole Diameter
Drilling Problems
Weather

Time
Equipment
Water Level
–Initials

Borehole diameter = 7"

FIGURE D.17

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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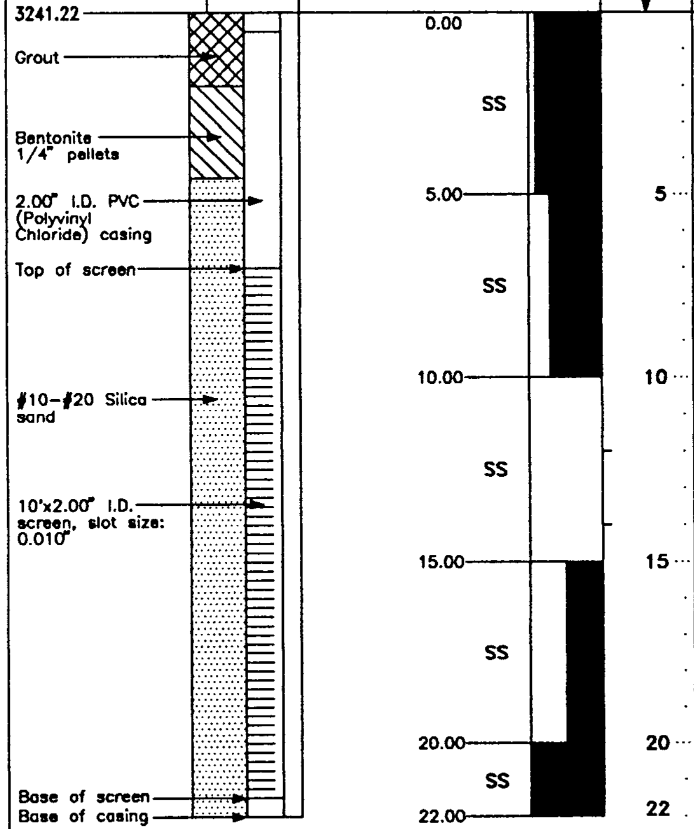
Date	09/26/94	ESTDATE	
Northing	1132950.38 ft.	NCOORD	
Easting	1156786.20 ft.	ECOORD	
Borehole Total Depth	22.00 ft.	DEPTH	
Establishing Company	ESCI	ESCCODE	
Drilling Company	HUNT	DRLCODE	
Drill Rig Type	HSA	DRLEQP	
Construction Method	HS	CMCCODE	
Air Force Installation	ELSWH	AFIID	
Location Identification	**MW-42**	LOCID	

Completion — Elevation feet MSL; Surface casing

Sampling — Instrument Reading Penetration; SBD / SED; SMCODE; REC% (100, 0)

Depth feet — Ground Surface



Lithology

USCS Unified Soil Classification System ASTMCODE	Lithologic Symbols & Codes LITHCODE	Description *SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. -Initials*	STRATORDER
ML		SILT, SAND and CLAY, 10YR6/4, little light yellowish brown, very fine grained sand, root material.	
CH		CLAY, 10YR4/3, brown, some silt, little fine-grained and very fine-grained sand, orange mottling.	
GC		SAND and GRAVEL, 705YR3/3, fine-grained to cobbled-sized gravel, little clay and silt, heavy iron staining.	
GC		Driller reports gravel at 8' BGL NO RECOVERY. Cable stuck in sampler. Cuttings indicate coarse gravel, sand and clay.	
CH		Driller reports shale at 14' BGL. CLAY SHALE, 5YR3/2, olive gray, slight fissility. Weathered. Fiberous crystals (selenite) in fractures.	
		CLAY SHALE, 5YR3/2, olive gray, slight fissility. Weathered. Fiberous crystals (selenite) in fractures.	

Remarks

Depth *Borehole Diameter* *Drilling Problems* *Weather*	*Time* *Equipment* *Water Level* *-Initials*
Borehole Diameter = 7"	

FIGURE D.18

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS
ENGINEERING SC[illegible]NCE, INC.
Denver, Colorado

Date	09/25/94	ESTDATE	Establishing Company	ESCI	ESCCODE	Air Force Installation	ELSWH	AFIID
Northing	1132921.16 ft.	NCOORD	Drilling Company	HUNT	DRLCODE	Location Identification	**BS-1**	LOCID
Easting	1156214.51 ft.	ECOORD	Drill Rig Type	HSA	DRLEQP			
Borehole Total Depth	22.00 ft.	DEPTH	Construction Method	HS	CMCCODE			

Completion

Elevation feet MSL

3248.76

Sampling

Instrument Reading Penetration	SBD – SED	SMCODE	REC%
	0.00 – 5.00	SS	
PID 8.00 ppm PID >300.00 ppm	5.00 – 10.00	SS	
PID >300.00 ppm	10.00 – 15.00	SS	
PID 300.00 ppm	15.00 – 20.00	SS	
	20.00 – 22.00	SS	

Depth

feet

Ground Surface

5, 10, 15, 20

Lithology

USCS Unified Soil Classification System ASTMCODE	Lithologic Symbols & Codes LITHCODE	Description SOIL/ROCK TYPE, modifiers/grain size, sorting, color, cement/lithification, moisture content, porosity, permeability/fracturing. –*Initials*	STRATORDER
ML	▨	CLAY and SILT, 10YR4/2, some very fine to fine-grained sand, abundant root material. –SP	
CH	▨	CLAY, 10YR4/2, extremely hard, little silt and very fine-grained sand.@5' SAA-increase in silt and very fine-grained sand. –SP	
CL	▨	CLAY, some silt and very fine-grained sand, HC stained, 5Y3/2 @8.07' SAA-little silt, trace of very fine-grained sand, 10YR4/3. –SP	
SM	░	SAND, fine to very fine-grained, little clay and silt, HC odor, little iron staining, clay increases with depth, 10YR5/3. –SP	
SC	░	SAND and CLAY, some silt, very fine-grained, trace of fine-grained, 10YR5/3. –SP	
GC	○	NO RECOVERY, cobble stuck in sampler shoe, driller reports gravel at 14.5 and shale at 17.5. –SP	
CH	▨	CLAY SHALE, trace of silt, very stiff, upper 1' is moist, orange mottling and iron staining, iron nodules, iron staining in fractures, slight weathering, 10YR3/2. –SP	

Remarks

Depth Borehole Diameter Drilling Problems Weather	Time Equipment Water Level –*Initials*

Borehole diameter = 6"

Boring hole abandoned and grouted to surface. –SP

FIGURE D.19

GEOLOGIC BOREHOLE AND WELL COMPLETION LOG

Engineering Evaluation/Cost Analysis
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Figure A.4

Well Development Record

WELL DEVELOPMENT RECORD

AFB		AFIID
Location identification	25	LOCID
Date	9/21/94	LOGDATE
Time		LOGTIME

Development Method

[✓ bail] pump surge air lift

other ____________

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

VOLUME MEASUREMENTS

Casing inside diameter	2 in
Static water level	15.7 ft
Total casing depth	21.78 ft
Length of water column	6.08 ft
PURGE VOLUME (calculated at bottom)	______ gal

6.08 · 0.16 = 0.97

6.08 · 4.08 = 24.8

Vol. annular = 24.8 − 0.97 = 23.8 ~~gal~~

23.8 · 0.30 = 7.14

Well Vol. = 7.14 + 0.97 = 8.1

Development volume = 6.08 ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) + (______ gals/ft. borehole volume - ______ casing volume) 0.30% porosity] = ______ gals.

PURGE RECORD

Time	Volume/~~Bail No.~~ (gal)	Temp ~~°F~~ (°C)	pH	Elec Cond (μMHOS)		Visual Appearance/Odor
9:24	0	10.2	7.39	850		Normal no vap
10:13	8	11.1	7.46	850		
10:58	16	11.8	7.52	850		
11:44	24	11.9	7.54	825		
12:29	32	12.3	7.47	850		

Weather: Stormy (Wind, rain, etc.)

Developed by: J. Johnson

Figure A.4
Well Development Record

MW26

WELL DEVELOPMENT RECORD

	AFB	AFID
Location identification	EAFB	MW26 LOCID
Date	9/28/94	LOGDATE
Time	______	LOGTIME

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

Development Method

[✓ bail] pump surge air lift

other ______________________

VOLUME MEASUREMENTS

Casing inside diameter 2 in
Static water level 24.68 ft
Total casing depth 30.89 ft
Length of water column 6.21 ft
PURGE VOLUME (calculated at bottom) ______ gal

6.21 (1.47) = 9.13
6.21 (.16) = 0.99
8.1
8.1 (.30) = 2.4 + 0.99 = 3.4
Well Vol. = 3.4 ft ≈ 3.5

Development volume = 6.21 ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) + (______ gals/ft. borehole volume - ______ casing volume) ____ % porosity] = ______ gals.

Very slow recharge in the early stage of development. Stopp after 2nd well volume to let well recharge. Recharge improved later in the day, but still slow.

PURGE RECORD

Time	Volume/Bail No.	Temp ~~°F~~ (°C)	pH	Elec Cond	Water Level (ft)	Visual Appearance/Odor
9:45	0/Initial	12.8	7.46	1850	24.68	Brown
10:09	3.5/1	12.6	7.49	1750		No odors
12:25	7/2	14.6	7.52	1725		detected.
15:53	10.5/3	13.8	7.52	1590		
16:16	14/4	13.3	7.50	1510		
17:24	17.5/5	13.4	7.59	1500	24.90	Light brown

Weather: Sunny + Warm Developed by: Jim Johnson

Figure A.4
Well Development Record

WELL DEVELOPMENT RECORD

AFB	EAFB	AFID
Location identification	MW 27	LOCID
Date	10/2/94	LOGDATE
Time		LOGTIME

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

Development Method

[✓ bail] pump surge air lift

other ______

VOLUME MEASUREMENTS

Casing inside diameter 2 in
Static water level 28.98 ft
Total casing depth 35.40 ft
Length of water column 6.420 ft
PURGE VOLUME (calculated at bottom) ______ gal

6.42 (1.47) = 9.44
6.42 (0.16) = 1.0
8.44 (.30) = 2.5
+ 1.0
3.5 = well Volum

Development volume = ______ ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) + (______ gals/ft. borehole volume - ______ casing volume) ______ % porosity] = ______ gals.

Very slow recharge.

PURGE RECORD

	Time	Volume/Bail No.	Temp ~~°F~~ (°C)	pH	Elec Cond (umhos)	Water Level (ft)	Visual Appearance/Odor
	8:04	0/Initial	10.8	7.50	3050	28.98	Lots of fines
	8:23	3.5/ 1	10.9	7.46	2990		
10/2	16:10	7.0/ 2	10.9	7.55	3100		
10/3	15:14	10.5/ 3	10.3	7.48	3000	34.71	

Weather: (9/2) Cloudy + Windy + Cool

Developed by: Jim Johnson

Figure A.4
Well Development Record

MW-28

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

WELL DEVELOPMENT RECORD

AFB		AFID
Location identification	EAFB	LOCID
Date	9/27/94	LOGDATE
Time		LOGTIME

Development Method

[✓ bail] pump surge air lift

other

VOLUME MEASUREMENTS

Casing inside diameter ~~6~~ 2 in
Static water level 19.31 ft
Total casing depth 24.97 ft
Length of water column 5.66 ft
PURGE VOLUME (calculated at bottom) 3 gal

Development volume = 5.66 ft water column × [✓ 1]/2/3/4/5 borehole volumes (*circle one*) × [(0.16 gals/ft. casing vol.) + (1.47 gals/ft. borehole volume - 0.16 casing volume) 0.3 % porosity] = 3 gals.

5.66 [(0.16) + (1.47 - 0.16) 0.3]
5.66 [0.16 + 1.31 (0.3)]
5.66 (0.16 + 0.393)
3.13

PURGE RECORD

	Time	Volume/Bail No.	Temp °C	pH	Elec Cond	Water Level	Visual Appearance/Odor
	12:05	Initial	14.6	7.47	1400	19.31	Muddy / No Odor
Surge	12:24	1 / 3gal	13.6	7.43	1200		Muddy / No odor
	12:50	2 / 6gal	15.2	7.32	1100		" / "
	12:57	3 / 9gal	14.0	7.28	1000		Cloudy / "
	13:05	4 / 12gal	14.0	7.32	1000		" / "
	13:14	5 / 15gal	14.2	7.30	1000		" / "
	13:23	6 / 18gal	13.6	7.17	950		" / "
	13:30	7 / 21gal	14.0	7.26	900		Slightly Cloudy / "
	13:38	8 / 24gal	14.0	7.34	950		Slightly Cloudy / "
	13:42					19.31	

Weather: Warm, Partly Cloudy, Slight breeze Developed by:

Figure A.4

Well Development Record

MW-29

Diameter (Inches)	Volume (Gals/ft)
[✓ 2]	[✓ 0.16]
4	0.65
[✓ 6]	[✓ 1.47]
8	2.61
10	4.08
12	5.88
14	8.00

WELL DEVELOPMENT RECORD

AFB		AFIID
Location identification	EAFB	LOCID
Date	9/27/94	LOGDATE
Time		LOGTIME

Development Method

[✓ bail] pump surge air lift

other

VOLUME MEASUREMENTS

Casing inside diameter 2 in
Static water level 15.80 ft
Total casing depth 24.90 ft
Length of water column 9.10 ft
PURGE VOLUME (calculated at bottom) 5 gal

Development volume = 9.10 ft water column × [✓ 1]/2/3/4/5 borehole volumes (*circle one*) × [(0.16 gals/ft. casing vol.) + (1.47 gals/ft. borehole volume - 0.16 casing volume) 0.3 % porosity] = 5 gals.

[(0.16) + (1.47 - 0.16)0.3]
[0.16 + 0.393]
0.553 gal/ft
(0.553 gal/ft)(9.10) ≃ 5.0

PURGE RECORD

Surged w/ bailer (9:10–9:40)

Time	Volume/Bail No.	Temp ~~°F~~ °C	pH	Elec Cond	Water Level	Visual Appearance/Odor
9:10	Initial	13.0	7.13	950	15.80'	Very Cloudy / Slight Product Odor
9:40	1 / 5 gal	14.2	7.19	950		" / Product Odor
9:52	2 / 10 gal	13.9	7.23	800		Cloudy / "
10:05	3 / 15 gal	13.6	7.17	800		Slightly Cloudy / "
10:18	4 / 20 gal	13.6	7.14	800	16.90	Slightly Cloudy / "
10:40					15.81'	

Weather: Warm, Partly Cloudy, Slight Breeze

Developed by:

Figure A.4
Well Development Record

MW30

WELL DEVELOPMENT RECORD

AFB		AFID
Location identification	EAFB	LOCID
Date	9/28/94	LOGDATE
Time		LOGTIME

Development Method

[✓ bail] pump surge air lift

other

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

VOLUME MEASUREMENTS

Casing inside diameter 2 in
Static water level 20.94 ft
Total casing depth 29.64 ft
Length of water column 8.70 ft
PURGE VOLUME (calculated at bottom) 5 gal

6" 8.70(1.47) = 12.8
2" 8.70 (0.16) = 1.4
11.4 • 0.30 = 3.4
Well Vol. = 3.4 + 1.4 = 4.8
= 5 ga

Development volume = ______ ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) + (______ gals/ft. borehole volume - ______ casing volume) ____ % porosity] = ______ gals.

PURGE RECORD

Time	Volume/Bail No.	Temp (°C)	pH	Elec Cond	Water level (ft)	Visual Appearance/Odor
12:54	0 / 0	13.6	7.28	1550	20.94	
13:28	5 / 1	13.3	7.19	1300		
13:53	10 / 2	13.5	7.19	1200		
14:17	15 / 3	13.3	7.31	1200		
14:41	20 / 4	13.4	7.29	1200		
15:06	25 / 5	13.4	7.30	1200	20.98	

Weather: Sunny & warm

Developed by: Jim Johnson

Figure A.4
Well Development Record

MW 31

WELL DEVELOPMENT RECORD

AFB EAFB AFID
Location identification [illegible] LOCID
Date 9/27/94 LOGDATE
Time ______ LOGTIME

Development Method
[✓ bail] pump surge air lift
other ______

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

VOLUME MEASUREMENTS

Casing inside diameter 2 in
Static water level 18.01 ft
Total casing depth 29.04 ft
Length of water column 11.03 ft
PURGE VOLUME (calculated at bottom) ______ gal

$V_{Borehole} =$ [illegible]

$11.03 \cdot 1.47 = 16.2 - 1.7 = 14.5 \cdot .3 =$
4.35
$11.03 \cdot 0.16 = 1.7$

Development volume = 11.03 ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(0.16 gals/ft. casing vol.) + (1.47 gals/ft. borehole volume - 1.7 casing volume) 0.30 % porosity]
= 6.0 gals. $4.35 + 1.7 = 6.0$ gal

PURGE RECORD

Time	Volume/Bail No.	Temp °F	pH	Elec Cond	H2O Level	Visual Appearance/Odor
15:30	0	13.9	7.51	1100	18.01	~~[illegible]~~
15:59	6/1	13.7	7.46	1050		Strong HC odor
16:21	12/2	13.1	7.57	1000		"
16:50	18/3	13.1	7.71	975		"
17:28	24/4	13.0	7.53	910		"
17:59	30/5	12.4	7.60	950		"
18:30	36/6	12.1	7.61	900	18.04	"

Weather: Sunny & warm
Developed by: J. Johnson

Figure A.4

Well Development Record

WELL DEVELOPMENT RECORD

AFB	EAFB	AFIID
Location identification	MW32	LOCID
Date	10/2/94	LOGDATE
Time	______	LOGTIME

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

Development Method

[✓ bail] pump surge air lift

other ____________________

VOLUME MEASUREMENTS

Casing inside diameter 2 in
Static water level 26.34 ft
Total casing depth 30.73 ft
Length of water column 4.39 ft
PURGE VOLUME (calculated at bottom) ______ gal

4.39 (1.47) = 6.45
4.39 (0.16) = 0.70
5.75 (0.30) = 1.7
+0.70
Well Vol. = 2.4

Development volume = 2.4 ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) + (______ gals/ft. borehole volume - ______ casing volume) ____ % porosity] = ______ gals.

Very slow recharge

PURGE RECORD

Time	Volume/Bail No.	Temp ~~°F~~ (°C)	pH	Elec Cond (µMHOs)	Water Level (ft)	Visual Appearance/Odor
11:42	0/Initial	11.6	7.49	2490	26.34	
10/2/94 11:59	2.4 / 1	11.6	7.53	2490		
10/3/94 17:40	4.0 / 2	10.1	7.78	2300	29.97	

Weather (9/2) Cloudy, cool, & windy Developed by: Jim Johnson

Figure A.4
Well Development Record

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

WELL DEVELOPMENT RECORD

AFB EAFB AFID
Location identification MW33 LOCID
Date 9/30/94 LOGDATE
Time ____ LOGTIME
Fuel Storage area D

Development Method

[✓ bail] pump surge air lift

other ____

VOLUME MEASUREMENTS

Casing inside diameter 2 in
Ground Level Static water level 24.74 ft
Total casing depth 34.72 ft
Length of water column 9.98 ft
PURGE VOLUME (calculated at bottom) ____ gal

9.98 (1.47) = 14.7
9.98 (.16) = 1.6
13.1 (.30) = 3.93
+ 1.6
5.53

Development volume = 5.5 ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(____ gals/ft. casing vol.) + (____ gals/ft. borehole volume - ____ casing volume) ____ % porosity]
= ____ gals.

PURGE RECORD

Time	Volume/Bail No.	Temp ~~°F~~ (°C)	pH	Elec Cond (µMHOS)	Water level (ft)	Visual Appearance/Odor
9:00	0/Initial	11.4	7.61	510	24.74	Brown color - Lots of suspend particles
9:20	5.5/1	11.2	7.59	490		
9:41	11/2	11.3	7.68	450		
10:06	16.5/3	11.4	7.69	390		"
10:30	22/4	11.6	7.84	390		"
10:52	27.5/5	11.8	7.86	390		"
11:17	33/6	11.6	7.81	390	24.70	"

Weather: Cool & cloudy. Light rain-intermit.
Developed by: Jim Johnson

Figure A.4
Well Development Record

WELL DEVELOPMENT RECORD

AFB	EAFB	AFID
Location identification	MW34	LOCID
Date	9/30/94	LOGDATE
Time		LOGTIME

Fuel Storage area D

Development Method

[✓ bail] pump surge air lift

other

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

5.92 (4.08) = 24.2
5.92 (0.16) = 0.95
23.2 (0.30) = 7.0
+0.96
8.0

VOLUME MEASUREMENTS

Casing inside diameter 2 in
From Ground Level Static water level 23.70 ft
Total casing depth 29.62 ft
Length of water column 5.92 ft
PURGE VOLUME (calculated at bottom) 24 gal
Borehole diameter = 10"
Development volume = 8.0 ft water column × 1/2/3/4/5
borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) +
(______ gals/ft. borehole volume - ______ casing volume) ____ % porosity]
= ______ gals.

PURGE RECORD

Time	Volume/Bail No.	Temp °F	pH	Elec Cond		Visual Appearance/Odor
12:39	0 / Initial	12.0	7.56	900	23.70	Brown color
13:28	8 / 1	11.5	7.58	850		Strong HC odors
14:04	16 / 2	11.6	7.52	875		NAPL sheen on
14:35	24 / 3	11.7	7.65	850	24.20	water surface

Weather: Partly Cloudy - Cool Developed by: Jim Johnson

Figure A.4

Well Development Record

WELL DEVELOPMENT RECORD

AFB	EAFB	AFID
Location identification	MW35	LOCID
Date	9/30/94	LOGDATE
Time		LOGTIME

Fuel Storage area D

Development Method

[✓ bail] pump surge air lift

other ______

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

VOLUME MEASUREMENTS

Casing inside diameter 2 in

From: Ground Level Static water level 22.3 ft

Total casing depth 28.81 ft

Length of water column 6.51 ft

PURGE VOLUME (calculated at bottom) 36 gal

Borehole diameter = 10"

Development volume = 8.7 ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) + (______ gals/ft. borehole volume - ______ casing volume) ____ % porosity] = ______ gals.

6.51 (4.08) = 26.6
6.51 (0.16) = 1.0
25.6 (0.30) = 7.7
+1.0
8.7

PURGE RECORD

Time	Volume/Bail No.	Temp (°C)	pH	Elec Cond (μMHOs)	Water Level (ft)	Visual Appearance/Odor
15:33	0/Initial	12.4	7.35	975	22.30	NAPL sheen on
16:02	9 / 1	12.2	7.42	780		water surface +
16:34	18 / 2	12.1	7.45	800		HC odors. Hi
17:10	27 / 3	11.9	7.44	800		concentration
17:44	36 / 4	12.0	7.38	825	22.41	of suspended
						Particles

Weather: Partly Cloudy + cool

Developed by: Jim Johnson

Figure A.4

Well Development Record

WELL DEVELOPMENT RECORD

AFB	EAFB	AFID
Location identification	MW39	LOCID
Date	10/3/94	LOGDATE
Time		LOGTIME

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

Development Method

bail [✓ pump] surge air lift

other __________

VOLUME MEASUREMENTS

Casing inside diameter	4	in
Static water level	19.19	ft
Total casing depth	21.37	ft
Length of water column	2.18	ft
PURGE VOLUME (calculated at bottom)		gal

2.18(4.08) = 8.89
2.18(0.65) = 1.4
7.5(0.3) = 2.3
1.4
Well Vol = 3.7 gal

Development volume = ______ ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) + (______ gals/ft. borehole volume - ______ casing volume) ____ % porosity]
= ______ gals.

PURGE RECORD

Time	Volume/Bail No.	Temp ~~°F~~ (°C)	pH	Elec Cond (uMHOs)	Water Level (ft)	Visual Appearance/Odor
16:01	0 / Initial	11.3	7.37	1190	19.19	
16:27	3.7 / 1	11.1	7.71	1150		
16:44	7.4 / 2	11.1	7.79	1150		
17:10	11.1 / 3	11.2	7.81	1150	19.29	

Weather: Cloudy, cool, + windy

Developed by: Jim Johnson

Figure A.4

Well Development Record

Purge

WELL DEVELOPMENT RECORD

AFB	EAFB	AFID
Location identification	MW39	LOCID
Date	10/4/94	LOGDATE
Time		LOGTIME

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

Development Method

[✓ bail] pump surge air lift

other ________

VOLUME MEASUREMENTS

Casing inside diameter 4 in
Static water level ____ ft
Total casing depth ____ ft
Length of water column ____ ft
PURGE VOLUME (calculated at bottom) ____ gal

Well Vol. = 3.9 gal

Development volume = ____ ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(____ gals/ft. casing vol.) + (____ gals/ft. borehole volume - ____ casing volume) ____ % porosity]
= ____ gals.

PURGE RECORD

Time	Volume/~~Bail~~ W.V. No.	Temp °F	pH	Elec Cond		Visual Appearance/Odor
14:10	3.9/1					
14:26	7.8/2					
14:40	11.7/3					

Weather: Crappy !

~~Developed~~ Purged by: Jim Johnson

Figure A.4
Well Development Record

WELL DEVELOPMENT RECORD

AFB	EAFB	AFID
Location identification	MW 40	LOCID
Date	10/3/94	LOGDATE
Time		LOGTIME

Diameter (Inches)	Volume (Gals/ft)
2	0.16
4	0.65
6	1.47
8	2.61
10	4.08
12	5.88
14	8.00

Development Method

~~bail~~ [✓ pump] surge air lift

other ______

VOLUME MEASUREMENTS

Casing inside diameter 4 in
Static water level 17.21 ft
Total casing depth 21.94 ft
Length of water column 4.73 ft
PURGE VOLUME (calculated at bottom) ______ gal

4.73(4.08) = 19.3
4.73(0.65) = 3.1
16(0.30) = 4.8
+ 3.1
7.9 = 8 gal

Development volume = 8 ft water column × 1/2/3/4/5 borehole volumes (*circle one*) × [(______ gals/ft. casing vol.) + (______ gals/ft. borehole volume - ______ casing volume) ______ % porosity]
= ______ gals.

PURGE RECORD

Time	Volume/Bail No.	Temp ~~F~~ (°C)	pH	Elec Cond (μMHOS)	Water Level (ft)	Visual Appearance/Odor
9:06	0 / Initial	10.9	7.41	750	17.21	Opaque. Low concentration of fines. HC odor present. HC Sheen on H_2O surface
10/3 9:42	8 / 1	12.6	7.50	790		
10/4 15:08	16 / 2	12.0	7.13	750		
(5gal) 15:40	21 / 3	11.2	7.39	790	21.92	

Weather: Cloudy, cool, & windy Developed by: Jim Johnson

APPENDIX C

AQUIFER TEST DATA

APPENDIX C

AQUIFER SLUG TEST RESULTS

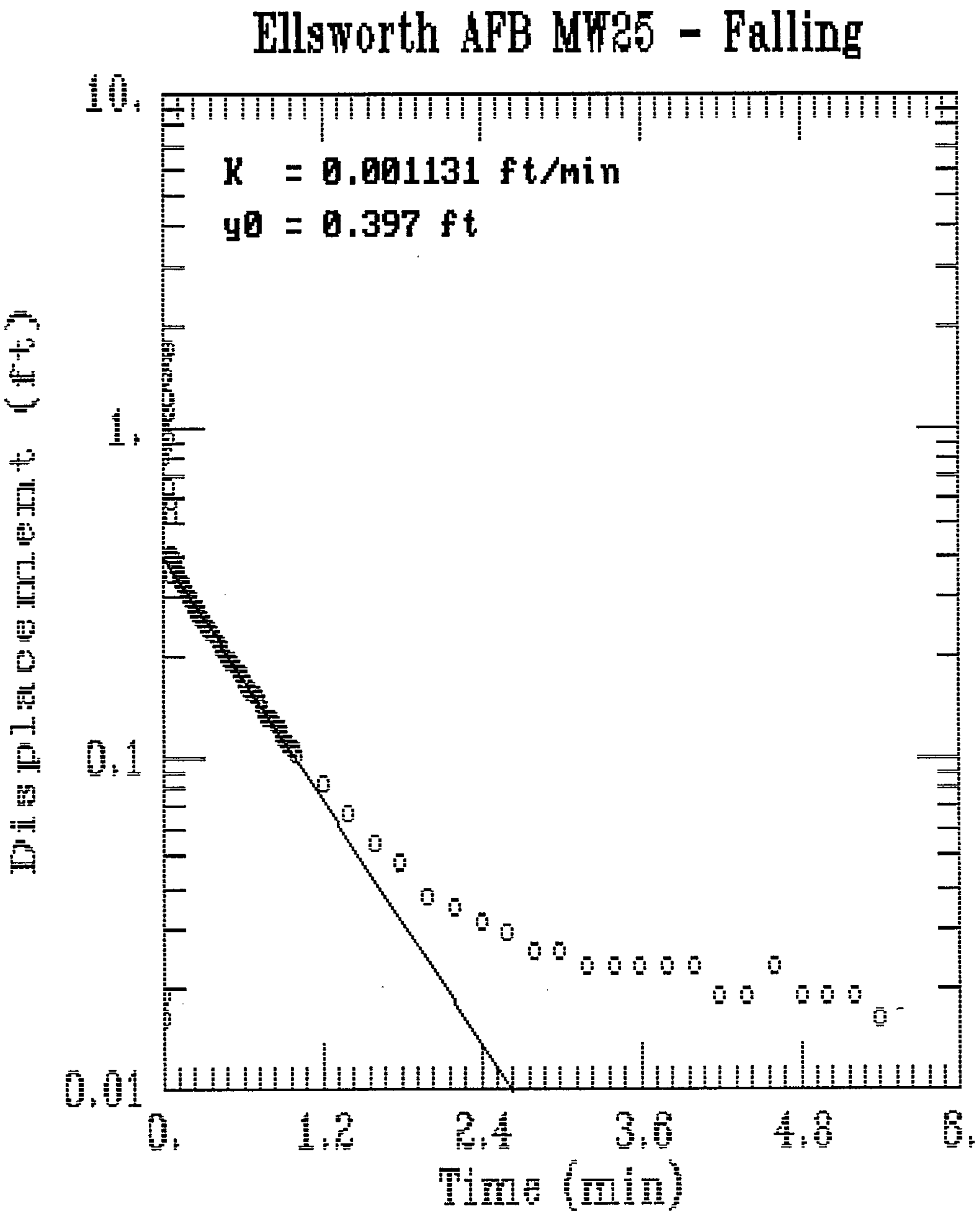
Aquifer slug tests were performed at Area D to estimate the hydraulic conductivity of saturated soils at the site. Slug tests are commonly performed in two steps, the falling head or slug in step and the rising head or slug out step. Both types of tests were performed at Area D. In a slug test, a slug of solid material or water is introduced into the well and water levels are monitored over time. This is the falling head portion of the test. Water levels will drop at the well returns to equilibrium. After the well has reached equilibrium the process is reversed during the rising head portion of the test. The slug is removed and water levels are again measured as the elevation head in the well increases. The rate at which the well returns to equilibrium is analogous to the hydraulic conductivity of the surrounding soils.

During the rising and falling head portions of a slug test, data is typically collected using a downhole pressure transducer and a data logger. For the testing performed at Area D a transducer and data logger manufactured by In Situ, Inc. were used (a Model PXD-260 transducer and a Model 1000B Hermit data logger). Data was collected at logarithmic time intervals and downloaded to a personal computer via a RS232 port.

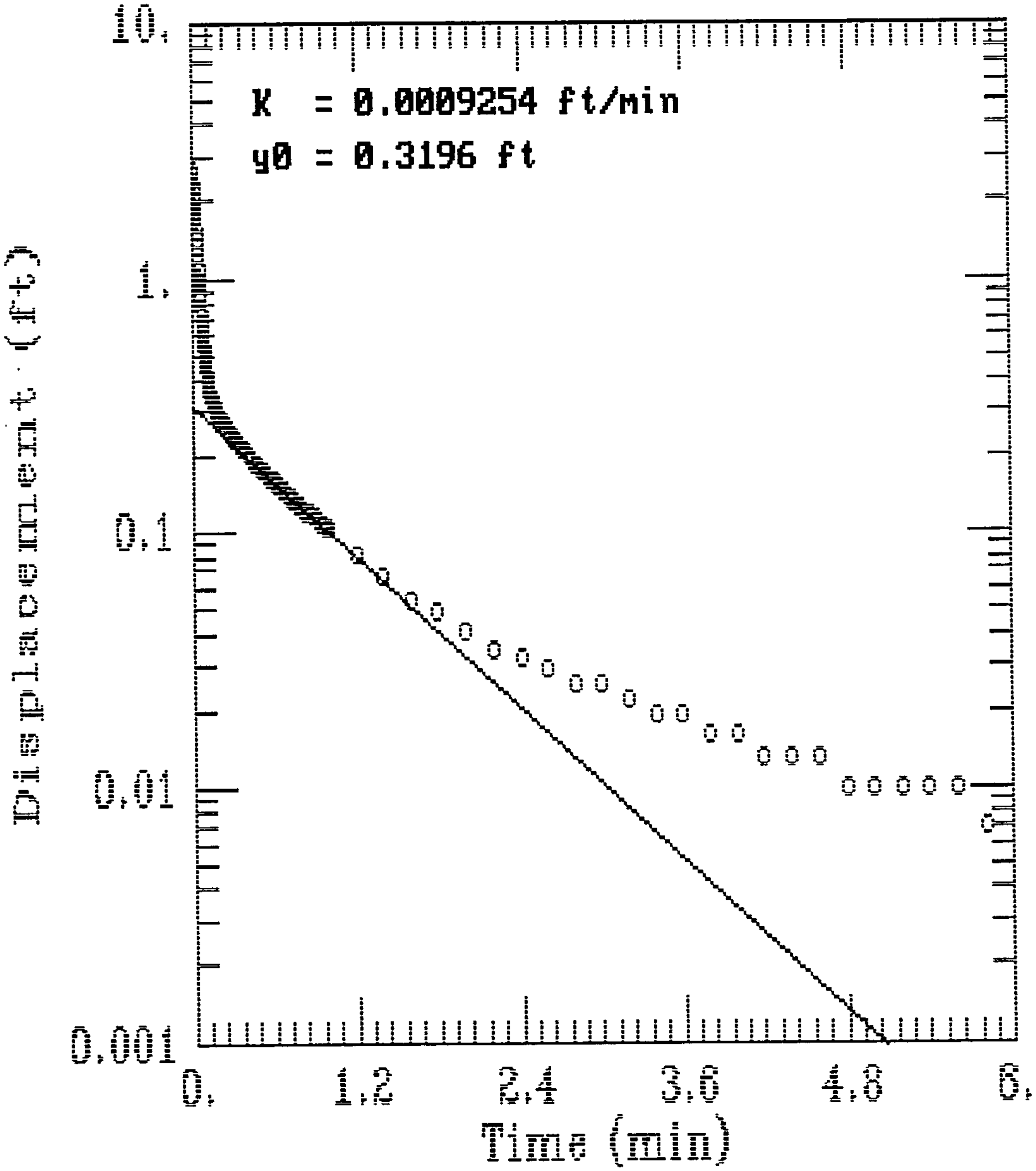
Data collected from the tests were analyzed using Aqtesolv® Version 1.10 software from Geraghty and Miller, Inc. Displacement (i.e., change in water level) was graphed logarithmically versus time and a linear best-fit line was applied visually. The slope of this line corresponds to the observed hydraulic conductivity. The graphical results of the tests are shown at the end of this appendix. Although both rising and falling head tests were performed and analyzed, it should be noted that falling head tests can provide erroneous results due to the fact that some water is displaced into the sandpack rather than the surrounding formation. This allows water levels to drop quickly, resulting in an apparent hydraulic conductivity that is greater than that of the surrounding soil. Results from the tests at Area D are shown in Table C.1.

TABLE C.1
SLUG TEST RESULTS
REMEDIAL ACTION PLAN
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

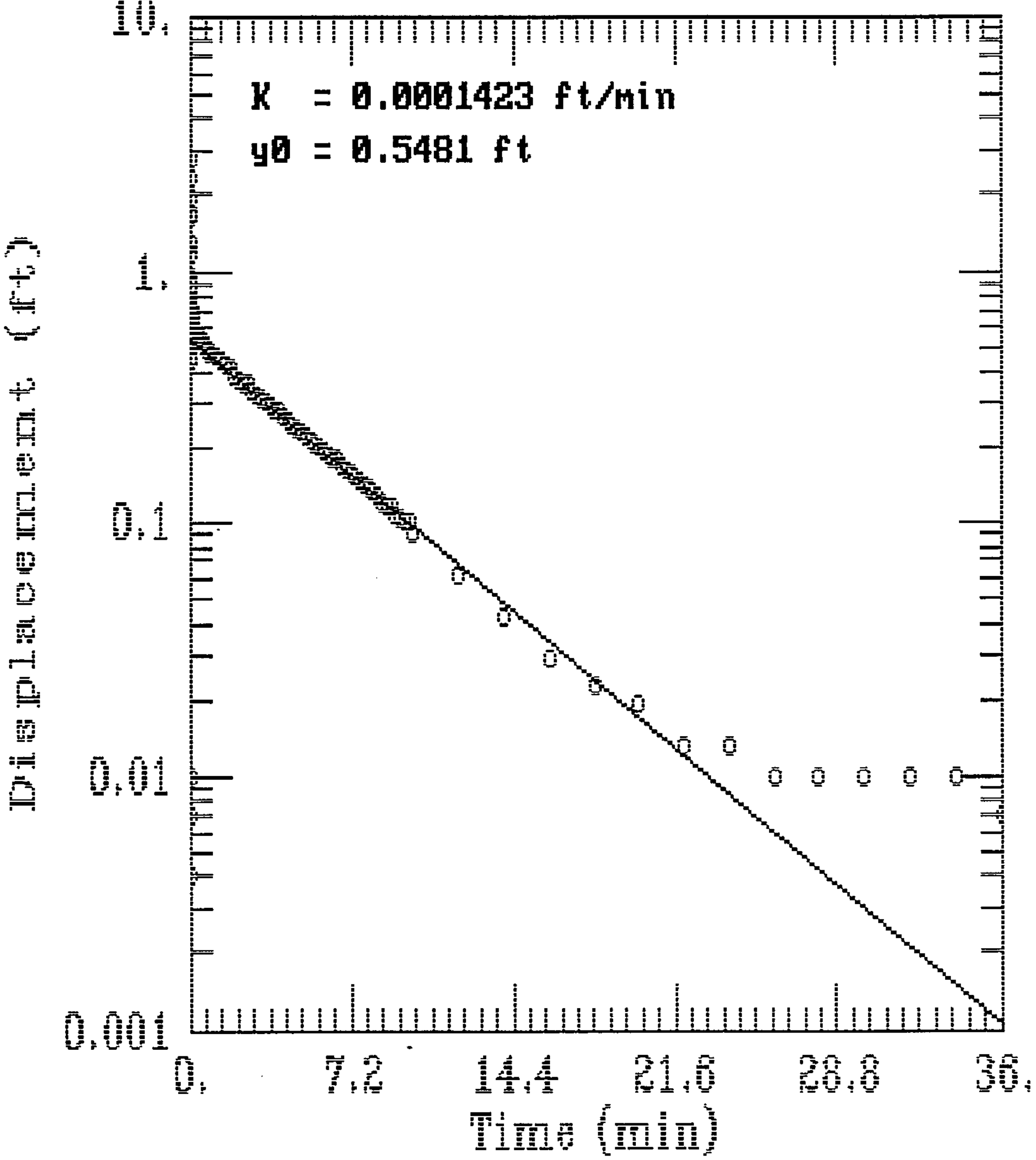
Well Number	Falling (ft/min)	Rising (ft/min)	Comments
25	0.00113	0.00092	
26	0.00014	0.00013	
28	0.00168	0.00236	
29	0.00025	0.00034	
30	0.0026	0.00499	
31	0.00052	0.00069	
33	0.00274	0.0262	Test questionable
34	0.00205	0.03745	Linear coefficients, test questionable
34	0.00214	0.01893	Quadradic coefficients, test questionable
35	0.00025	0.00052	


Ellsworth AFB MW25 - Falling
K = 0.001131 ft/min
y0 = 0.397 ft
Displacement (ft)
10.
1.
0.1
0.01
0.
1.2
2.4
3.6
4.8
6.
Time (min)

Ellsworth AFB MW25 - Rising



Ellsworth AFB MW26 - Falling



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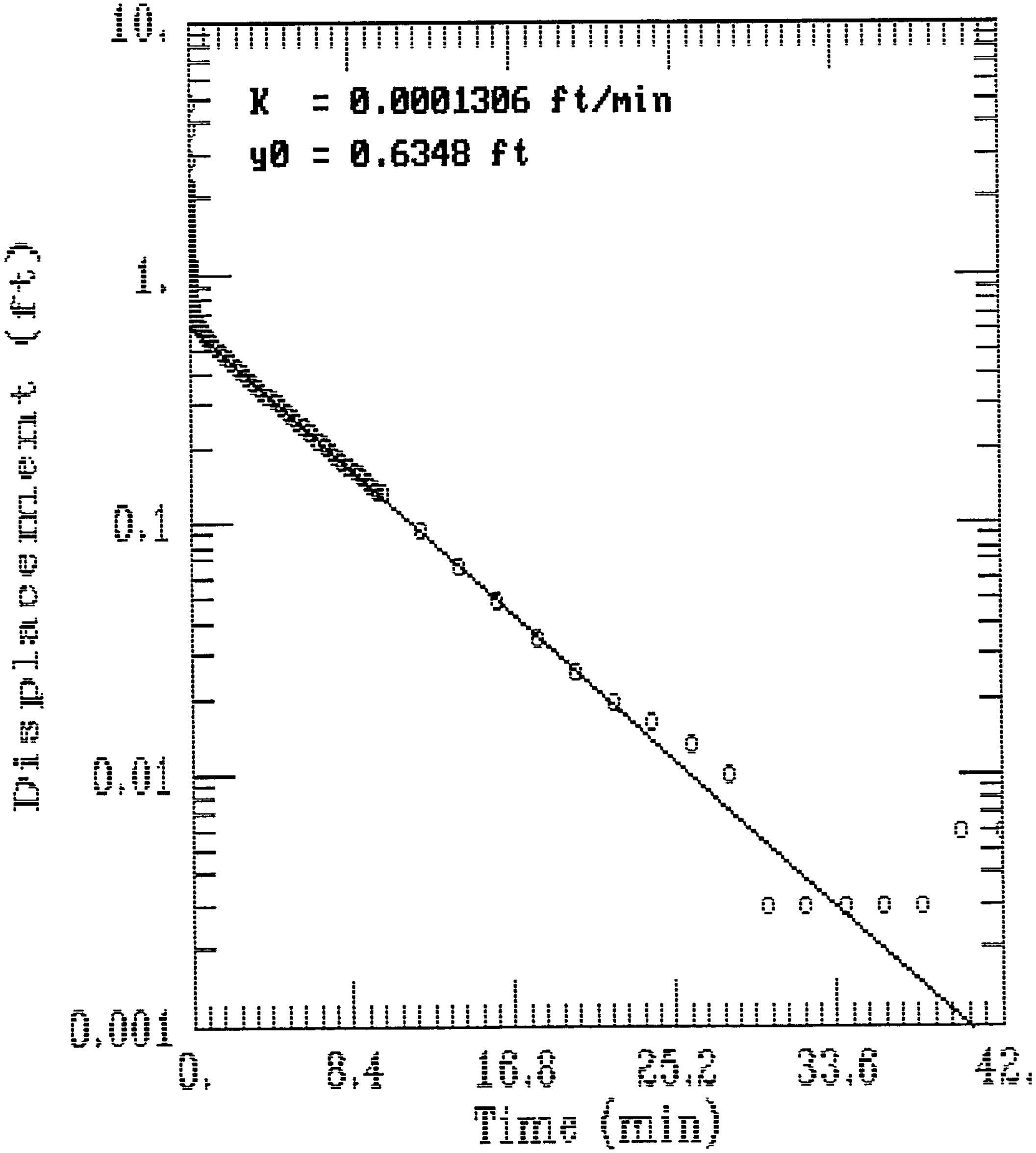

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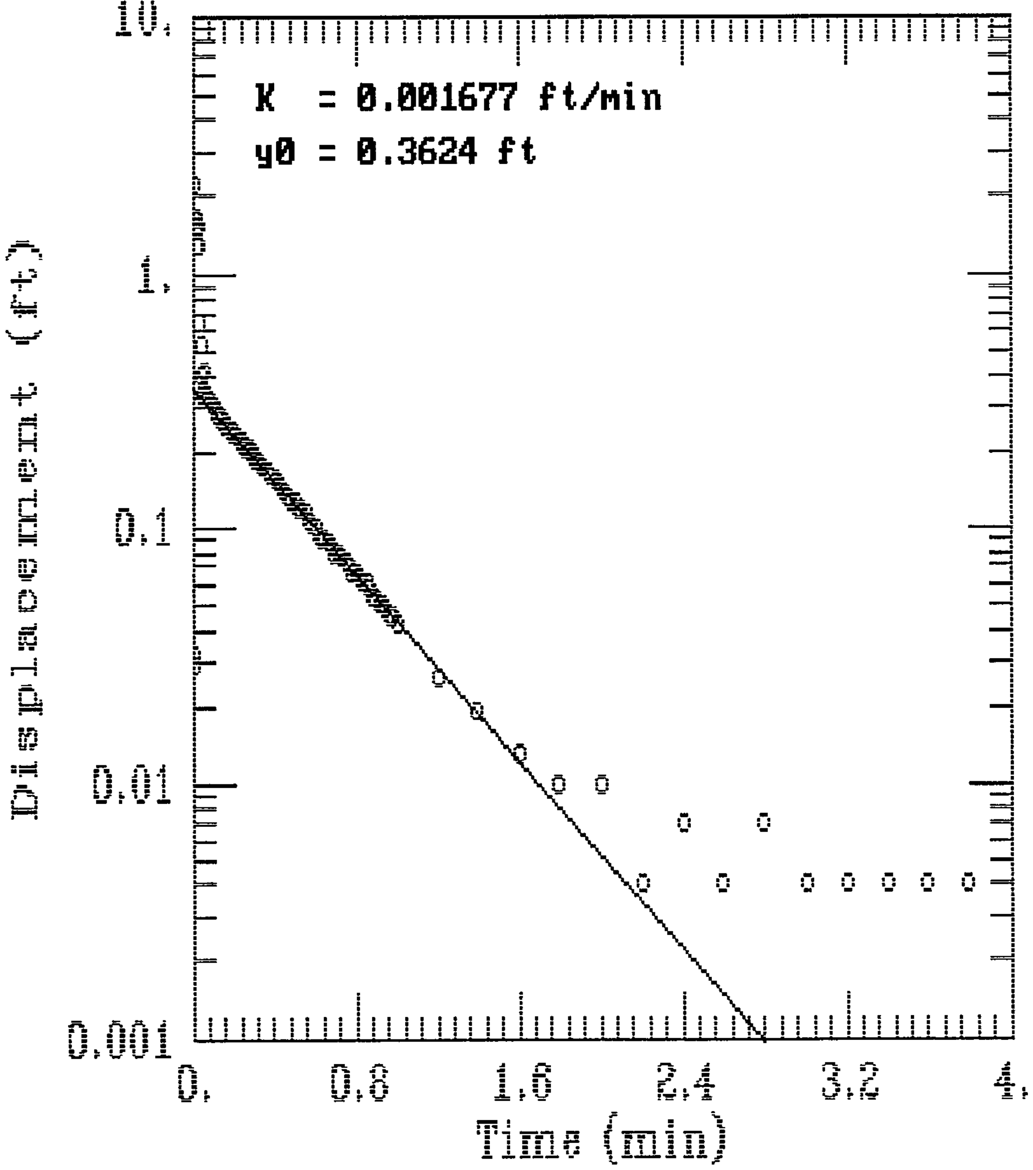

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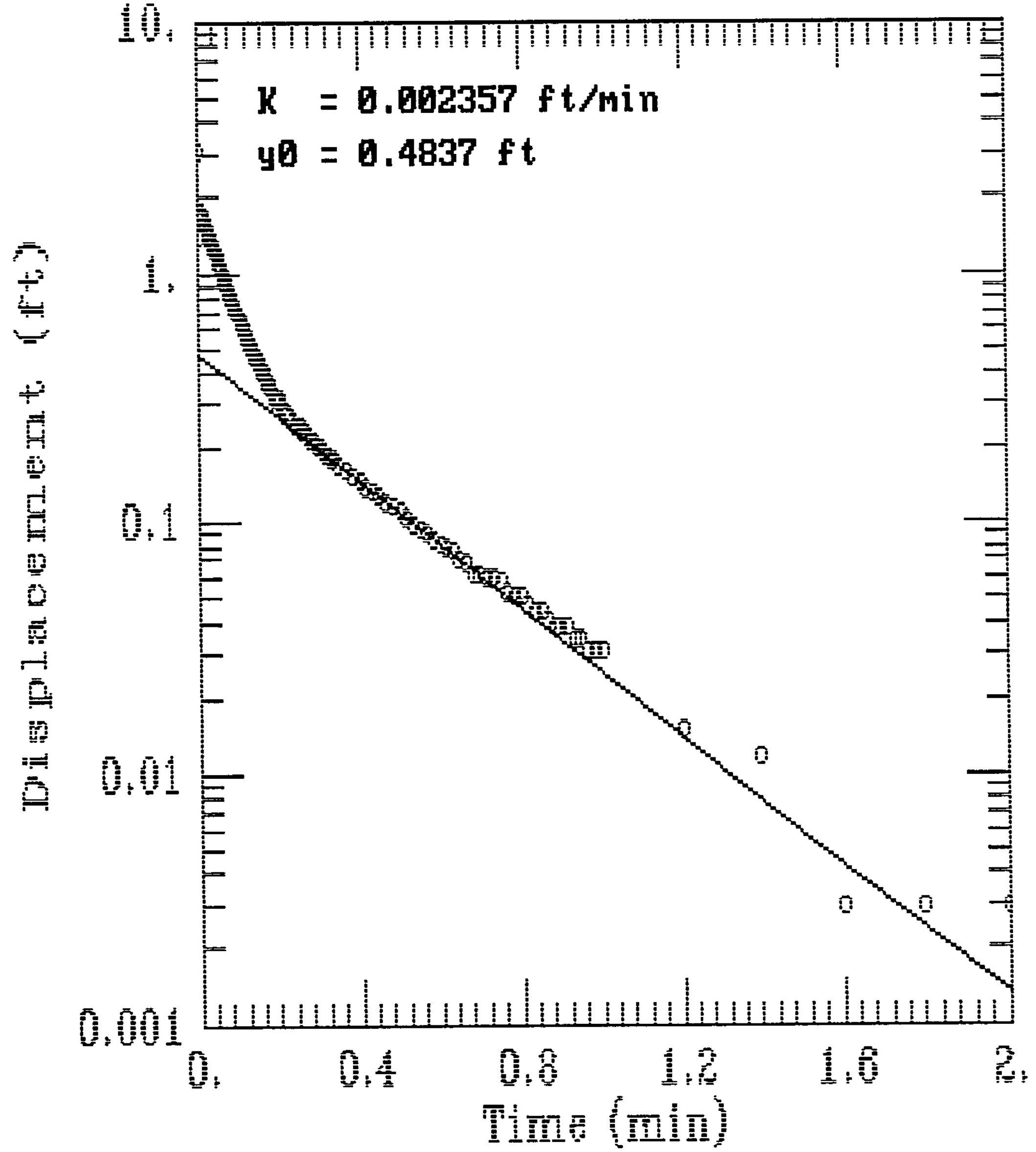

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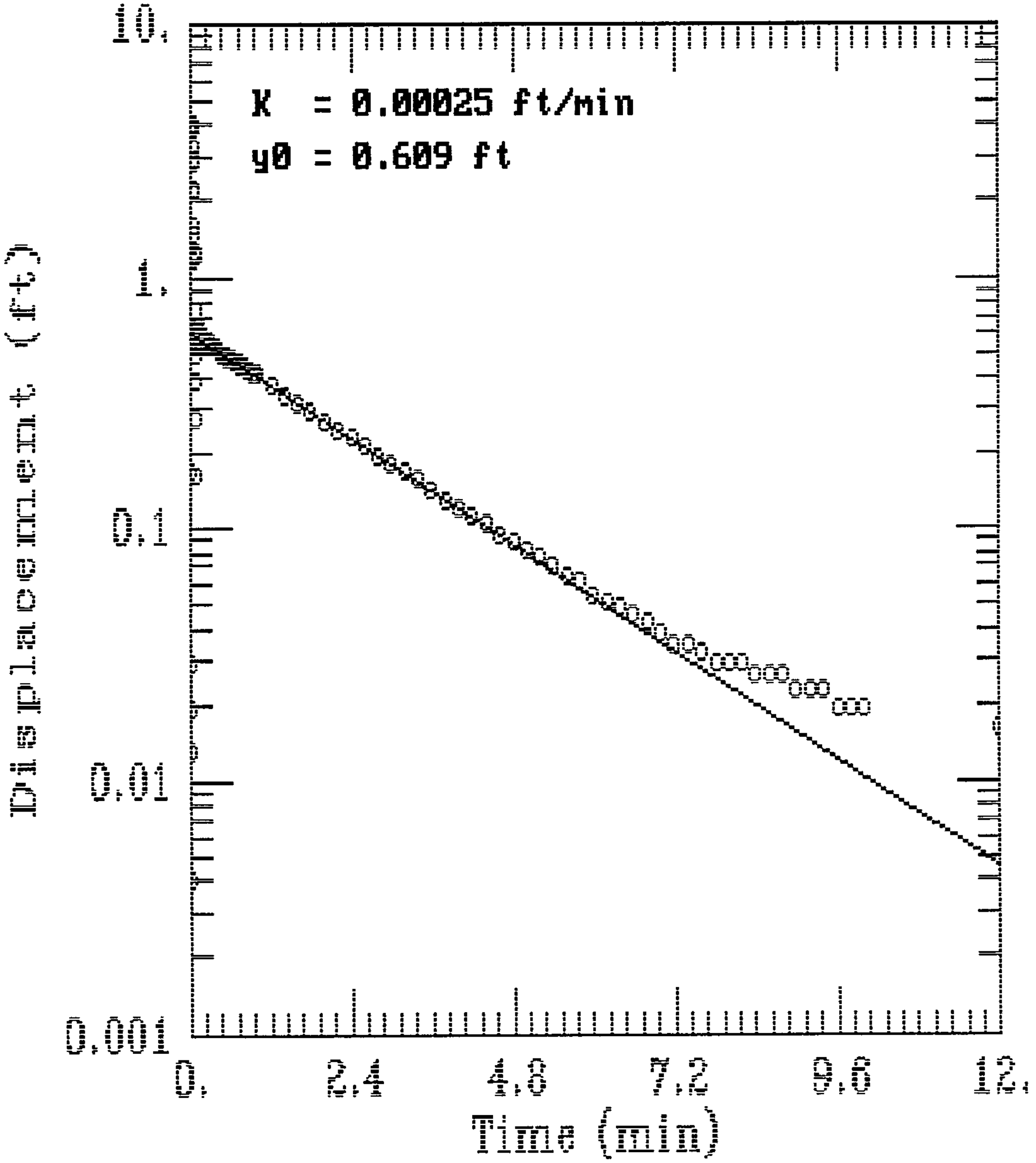

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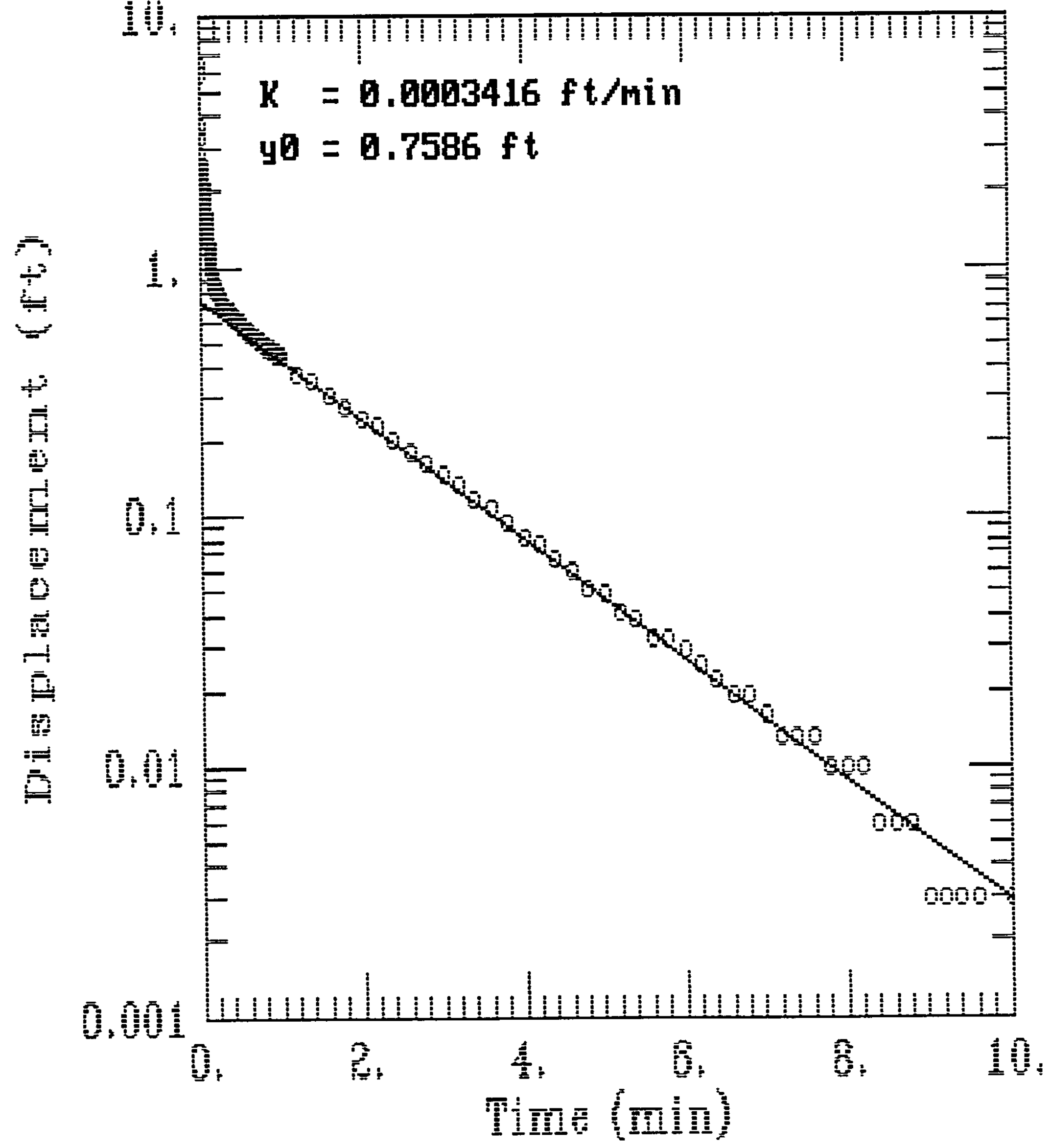

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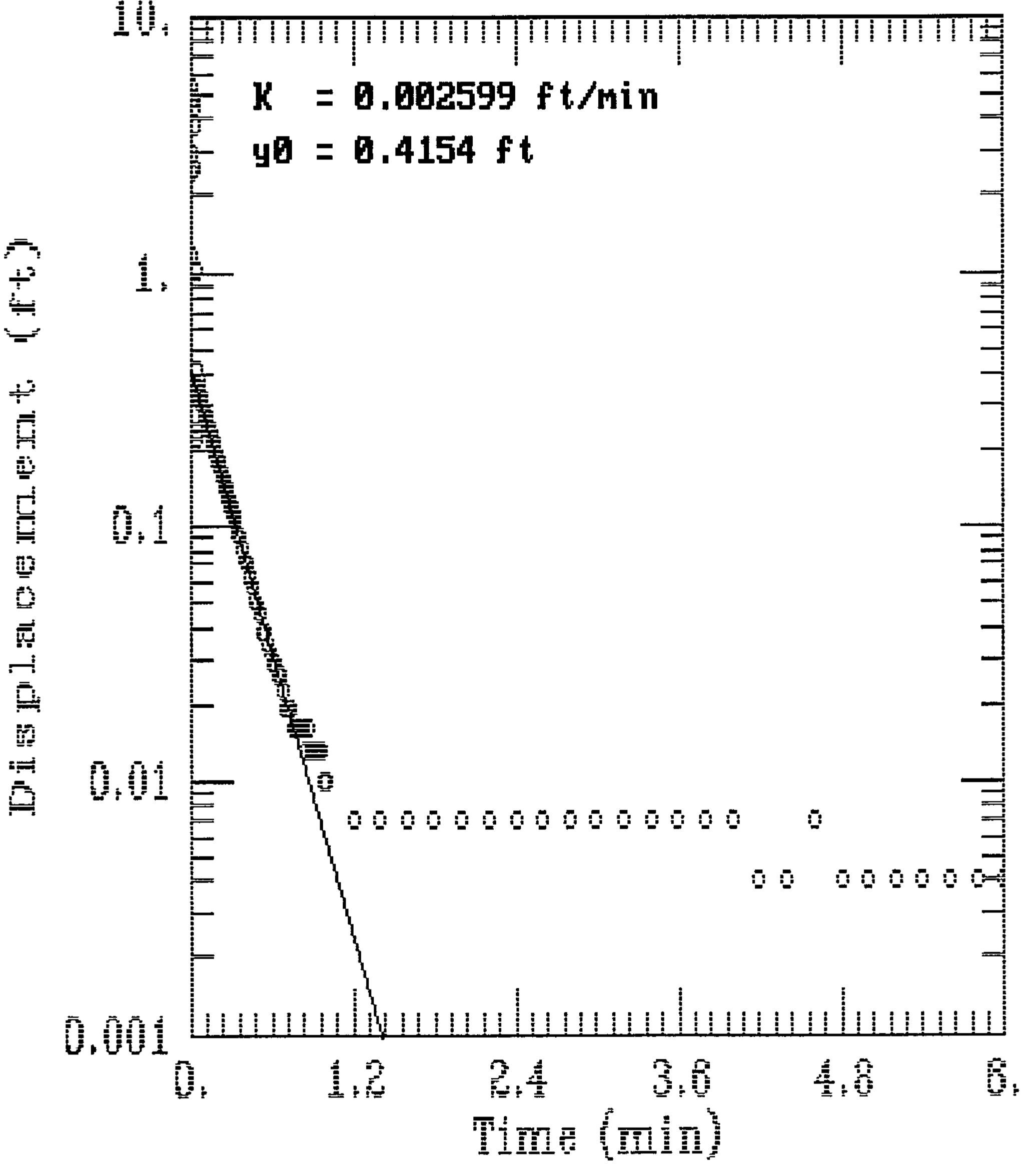

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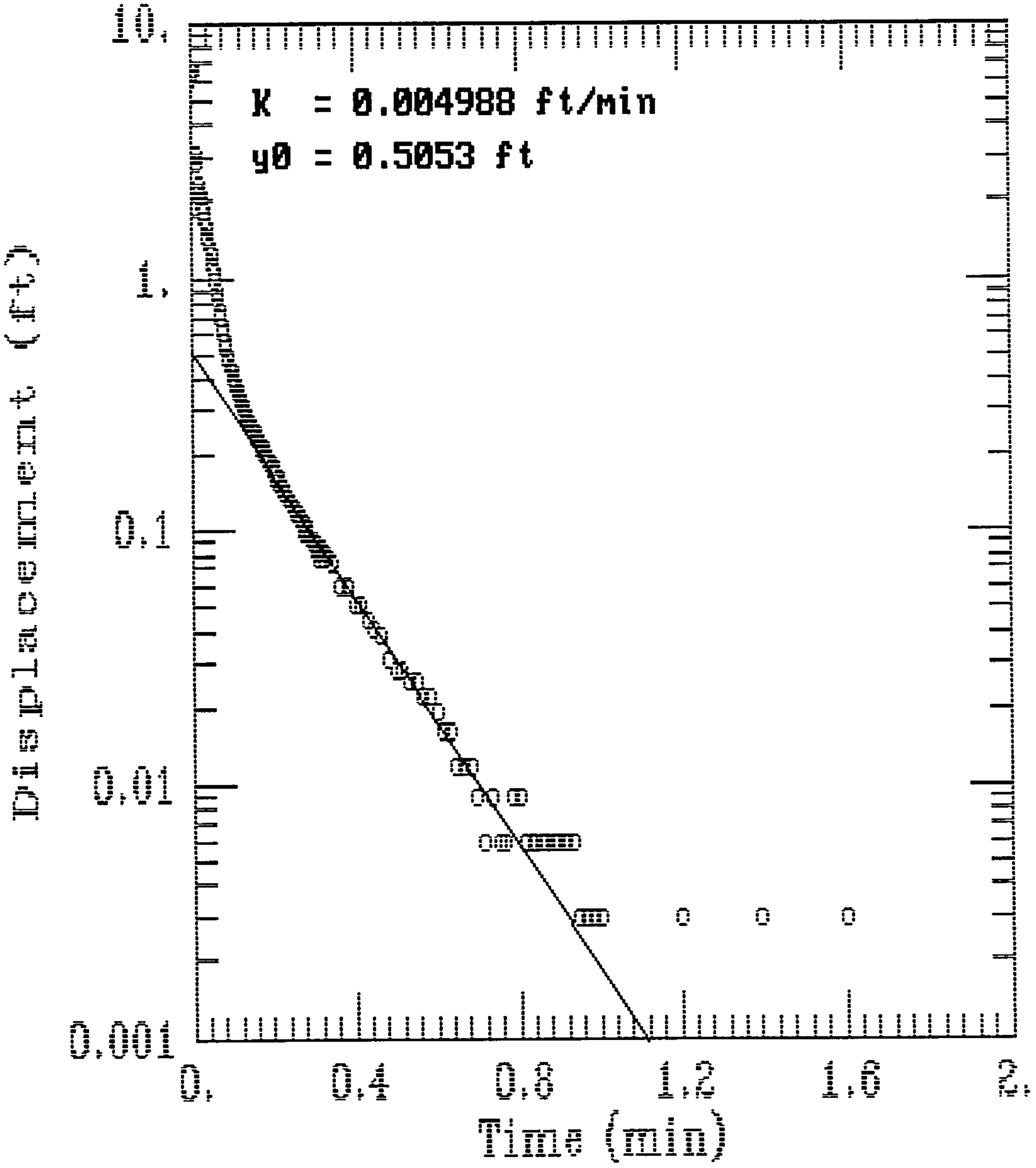
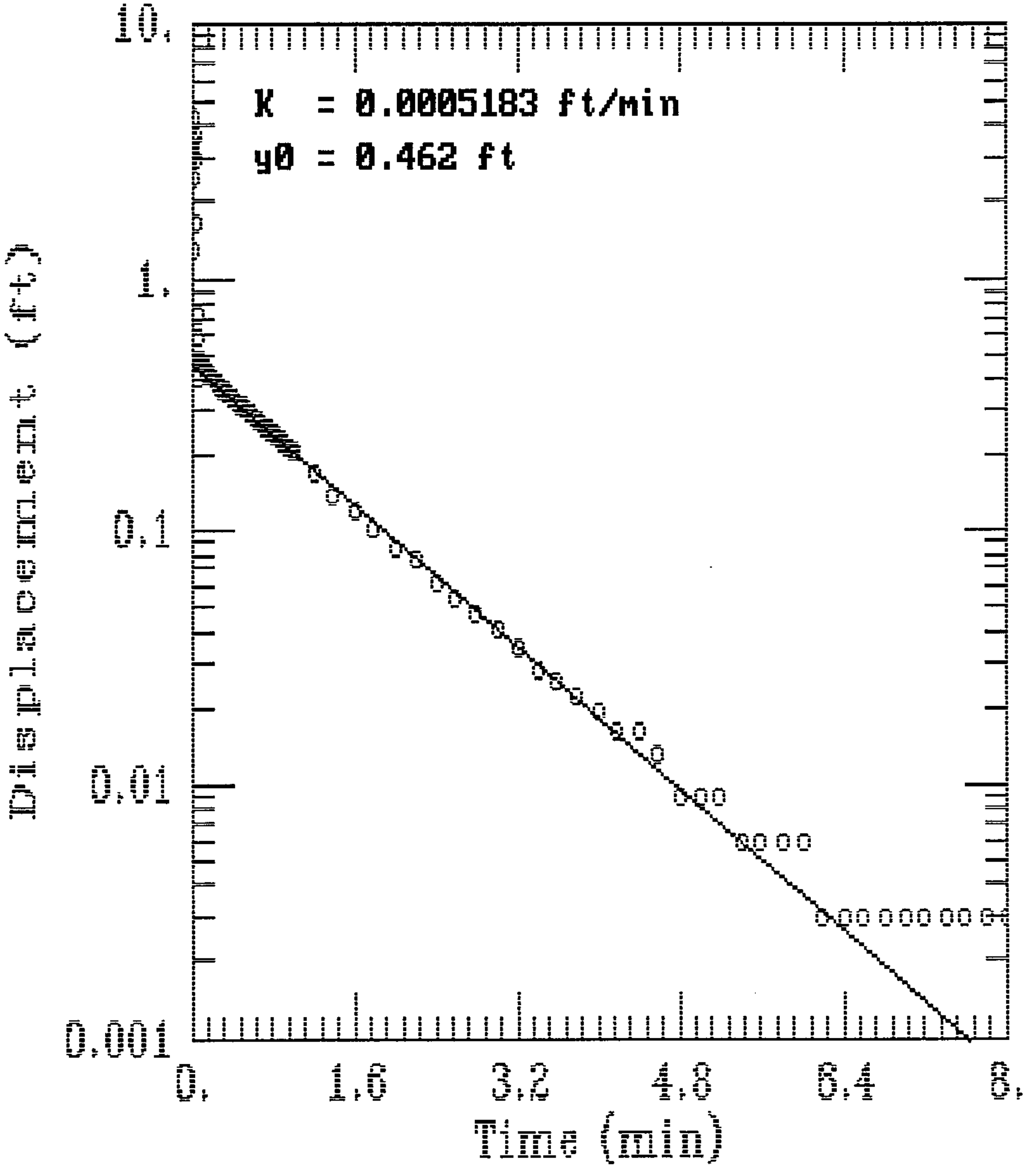


Ellsworth MW31 - Falling



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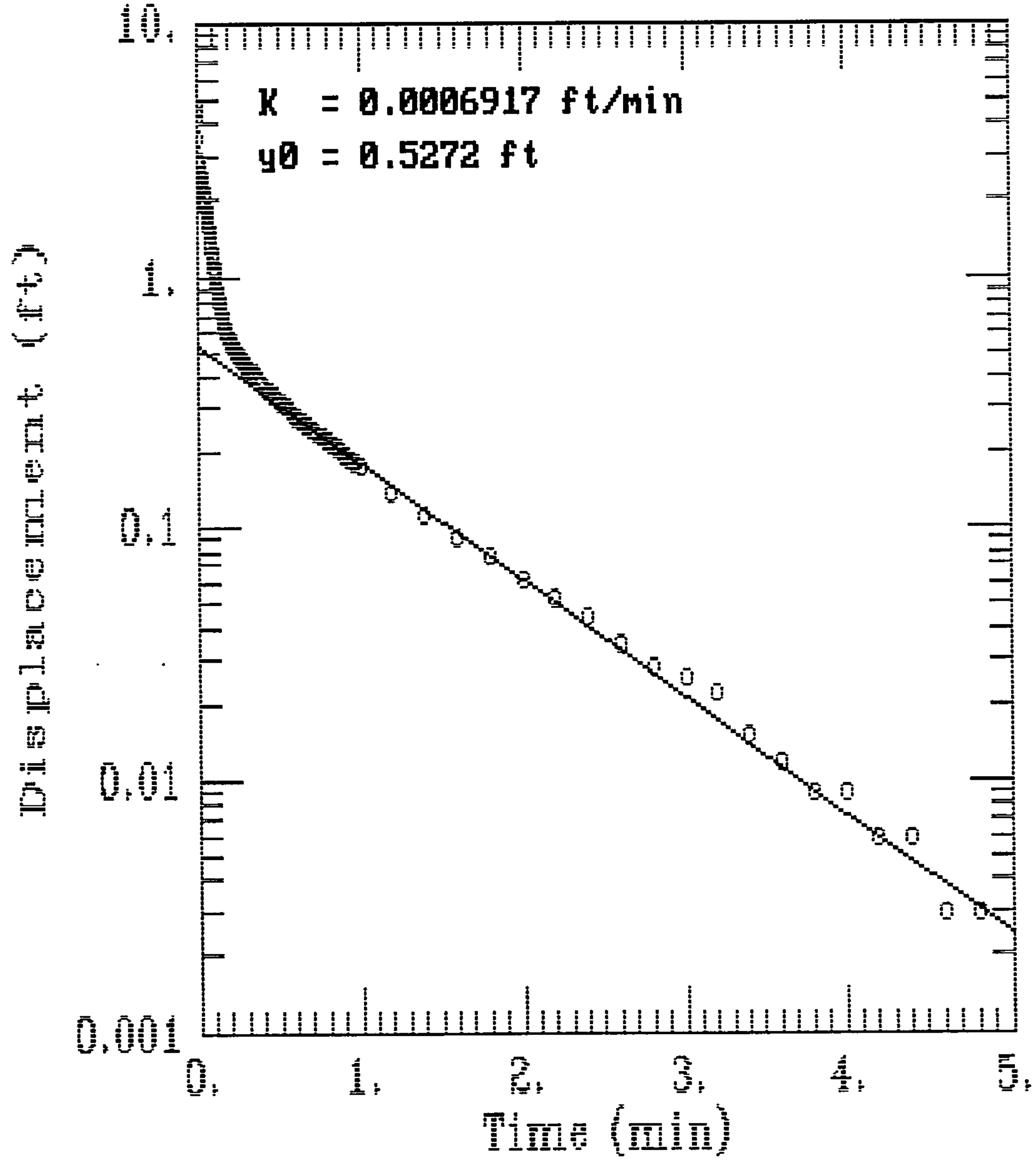

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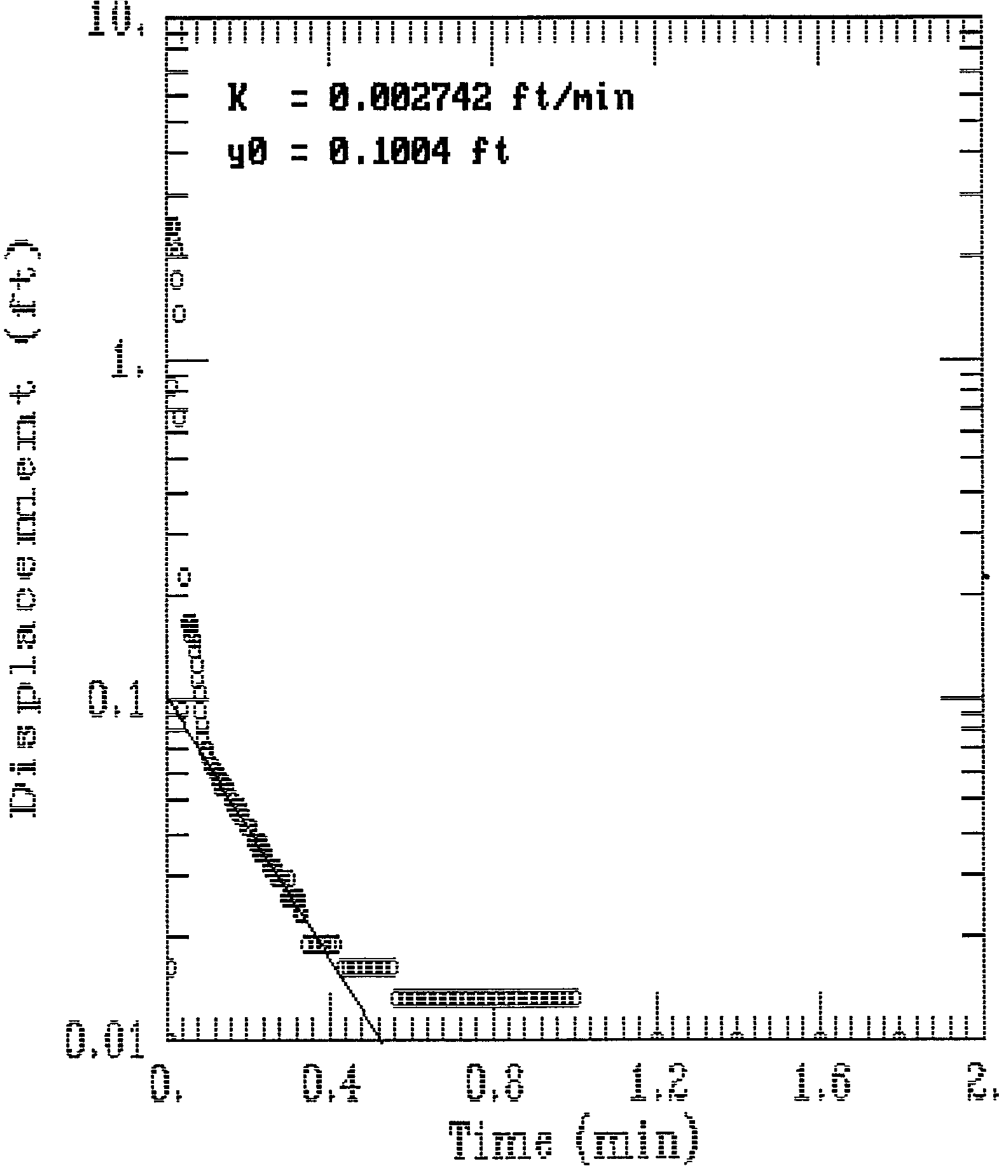

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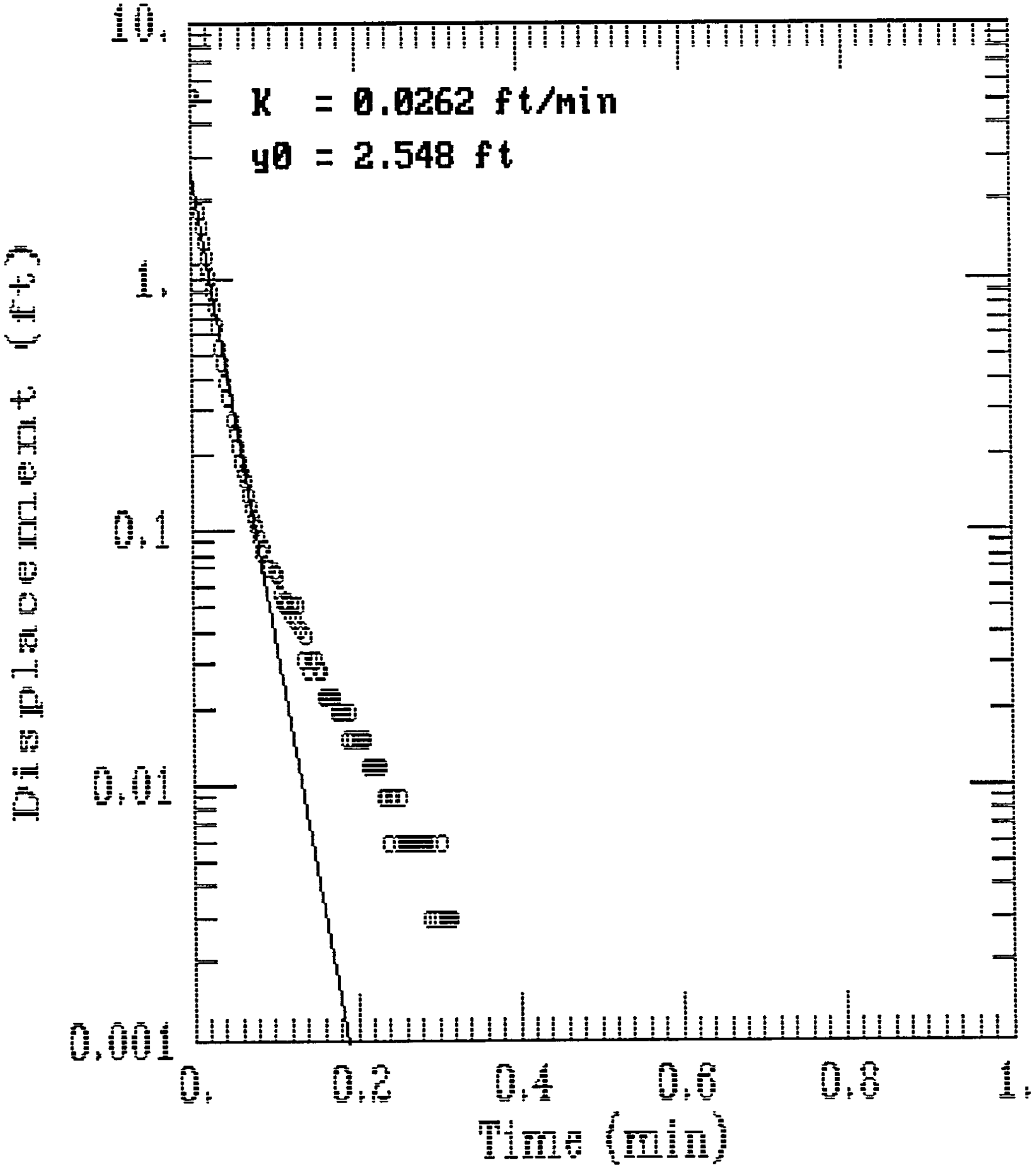
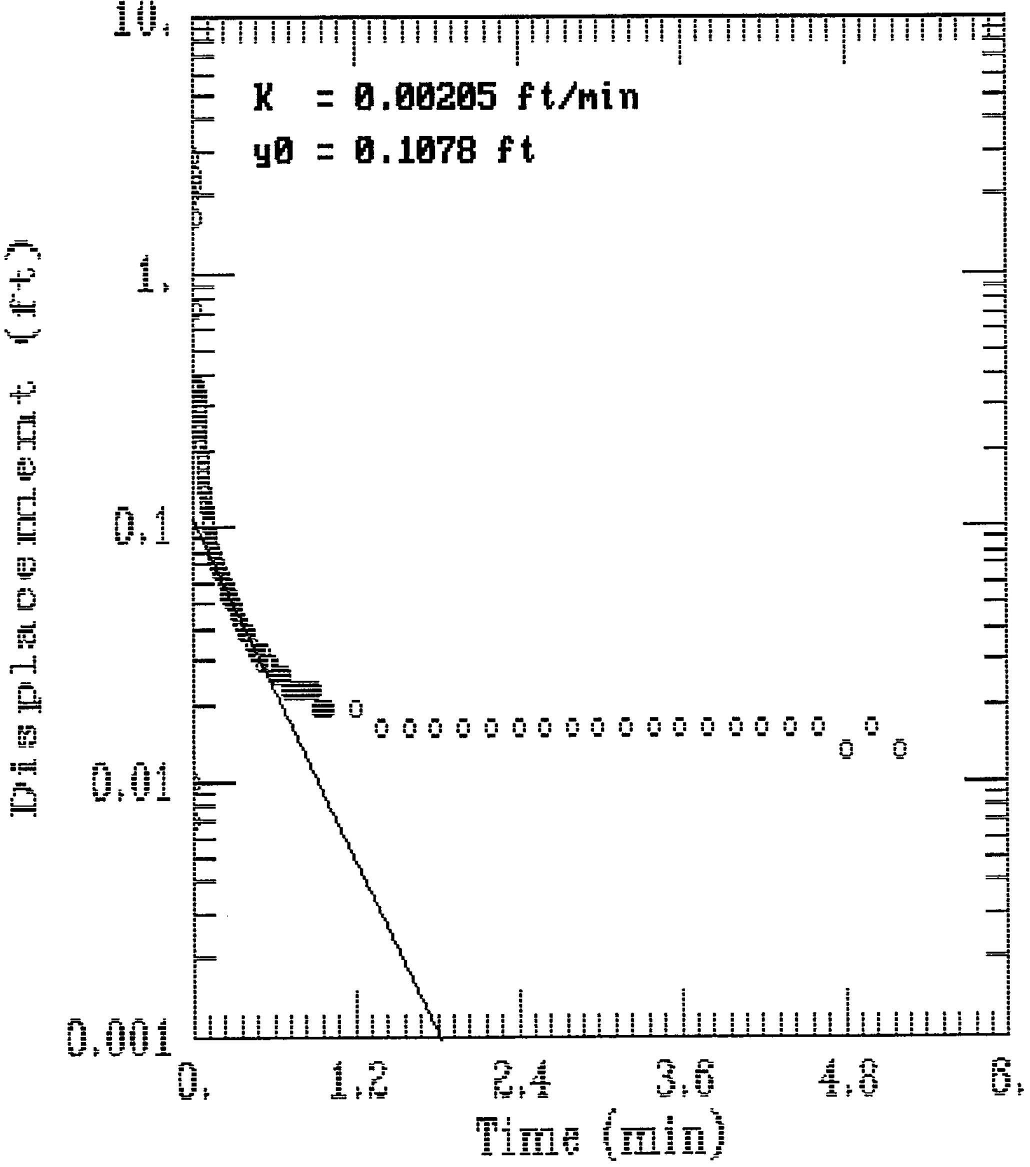
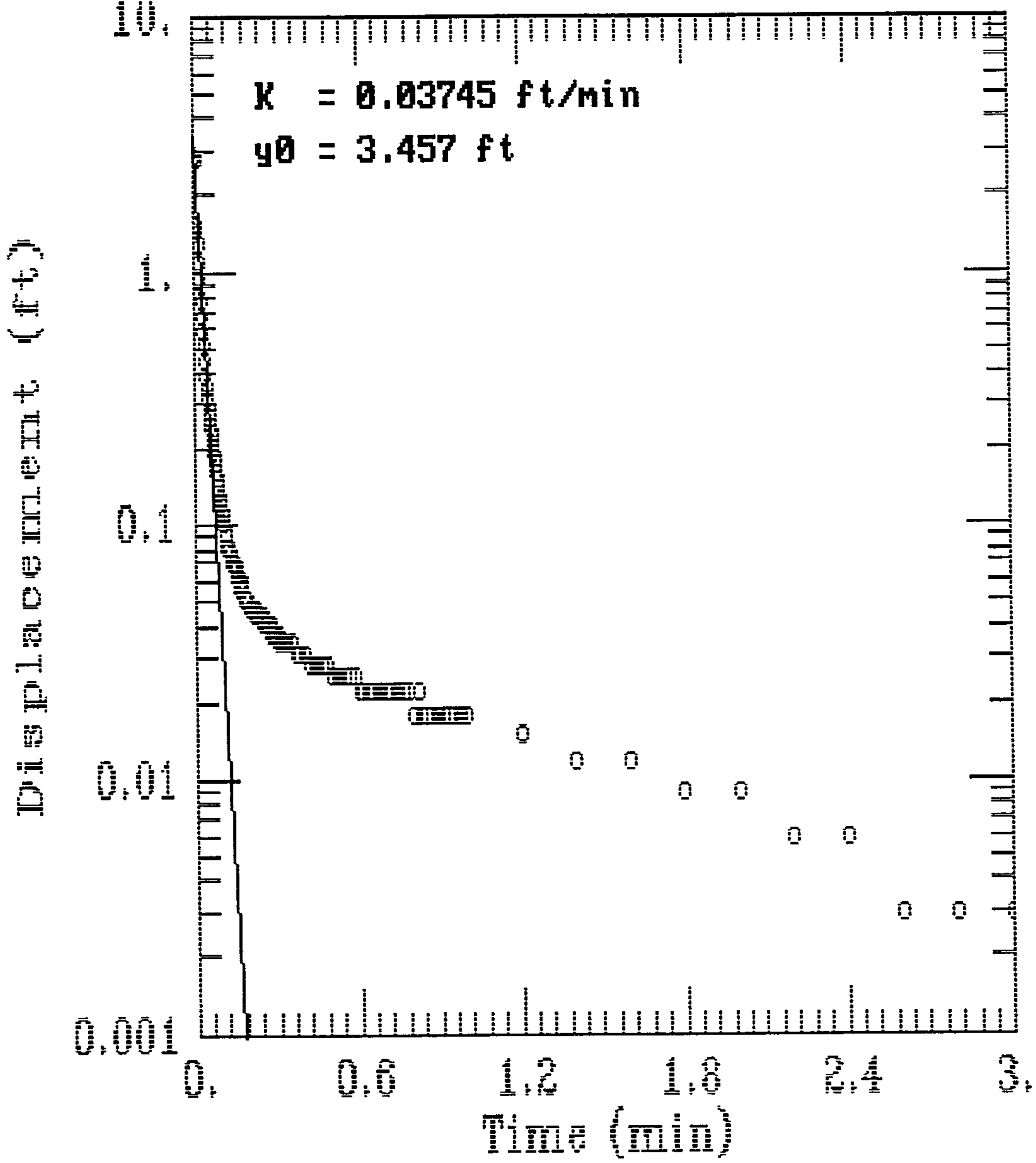


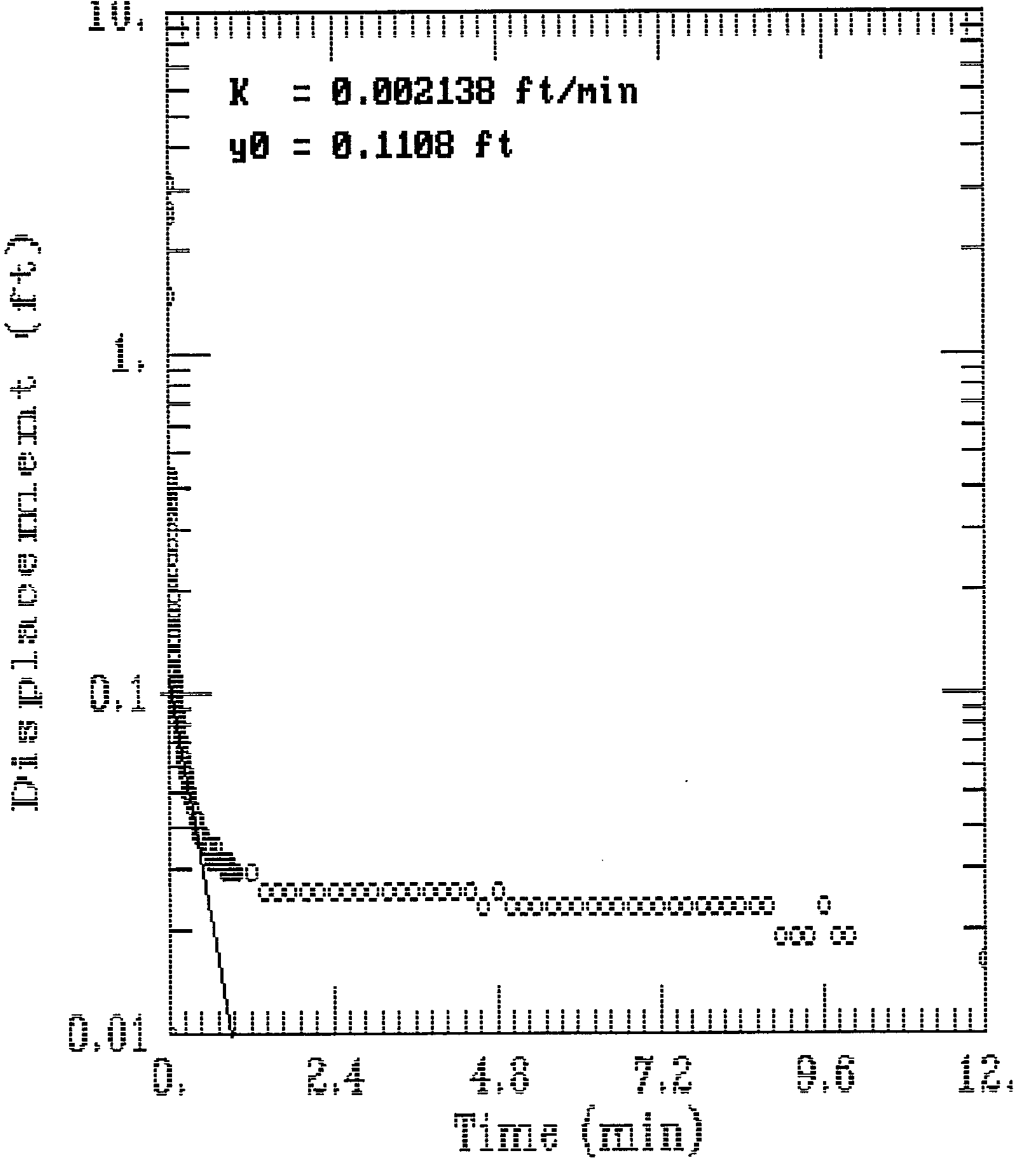
Ellsworth AFB MW34 - Falling - Linear



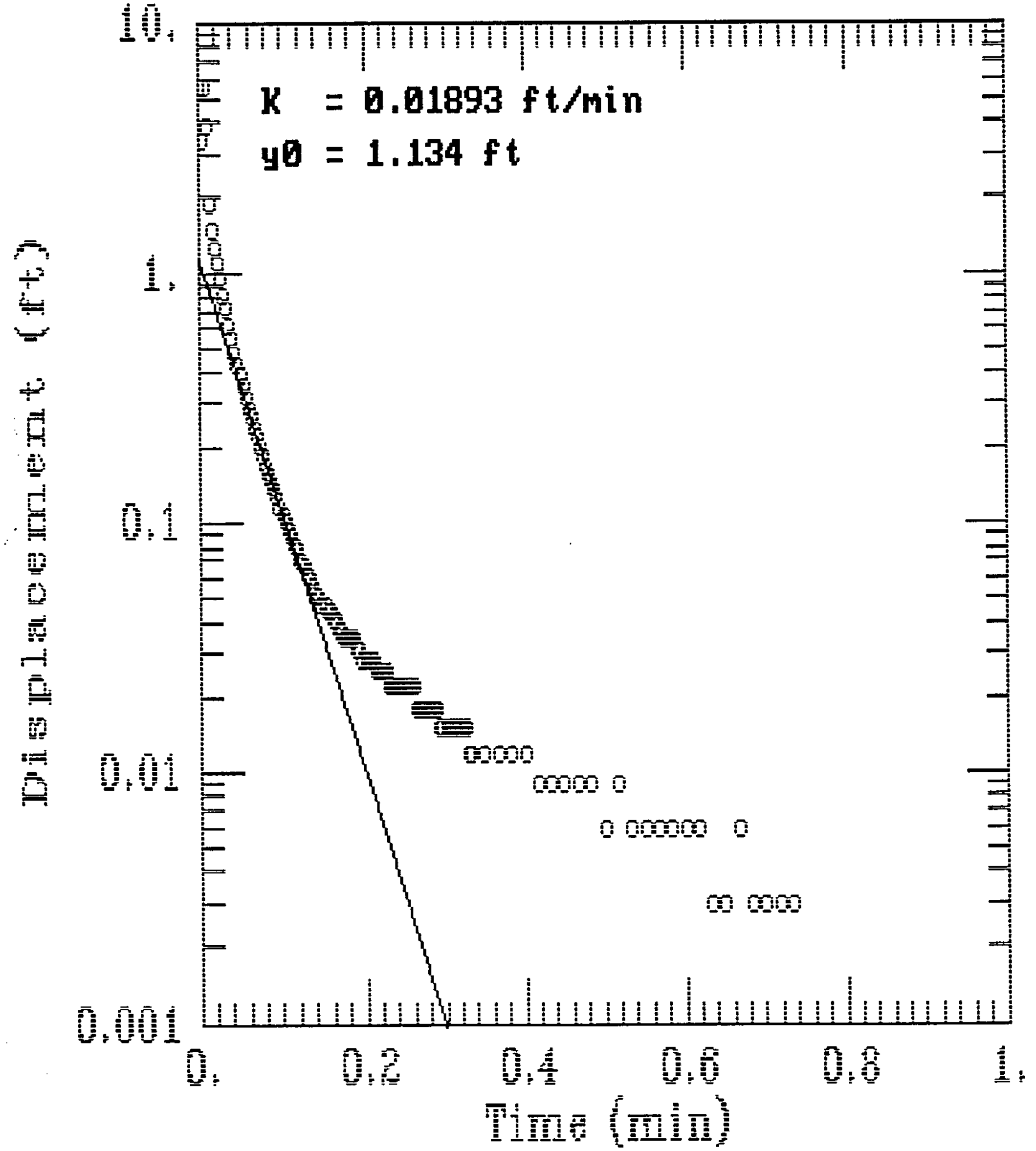
Ellsworth AFB MW34 - Rising - Linear



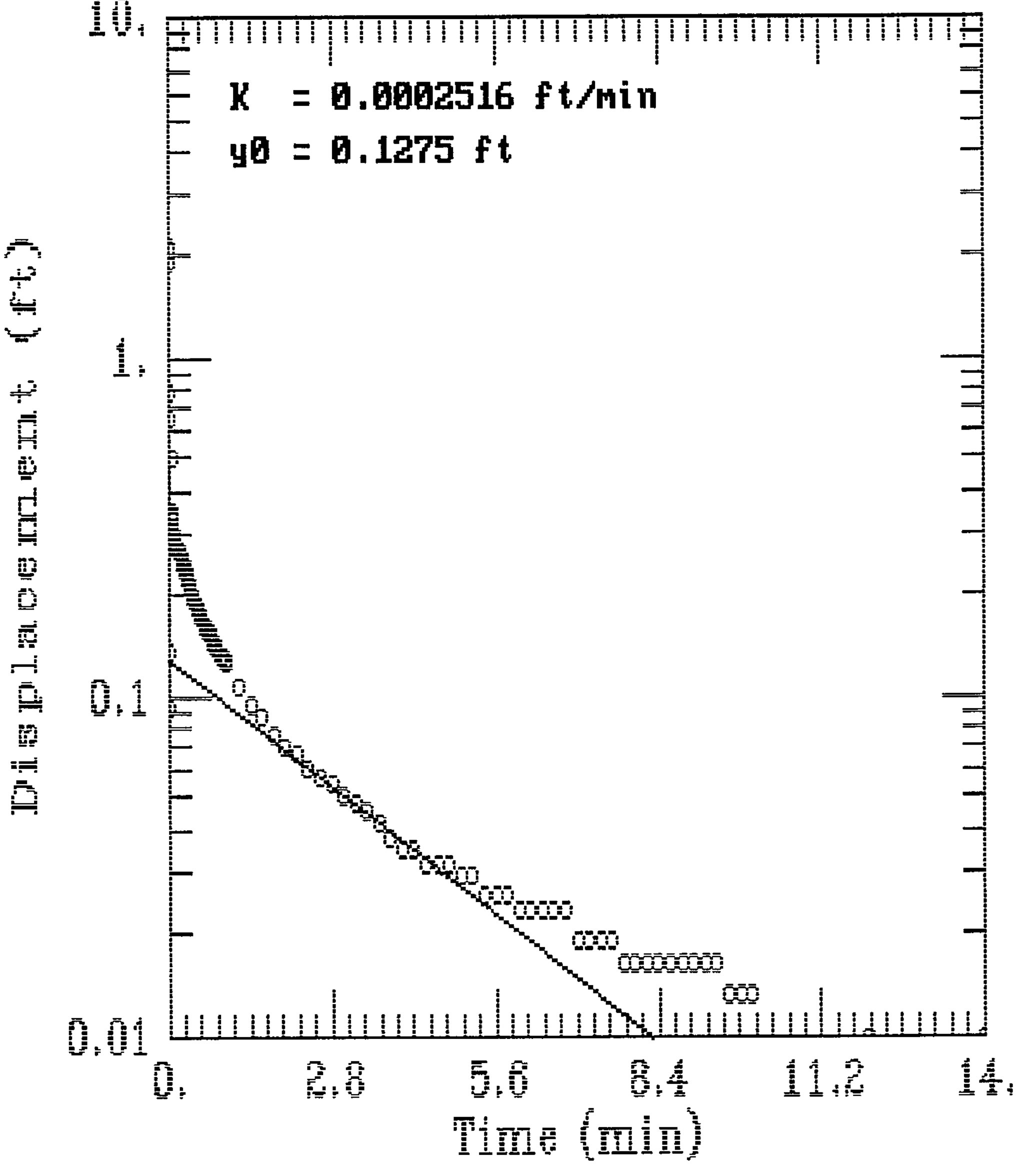
Ellsworth AFB MW34 - Falling - Quadradic



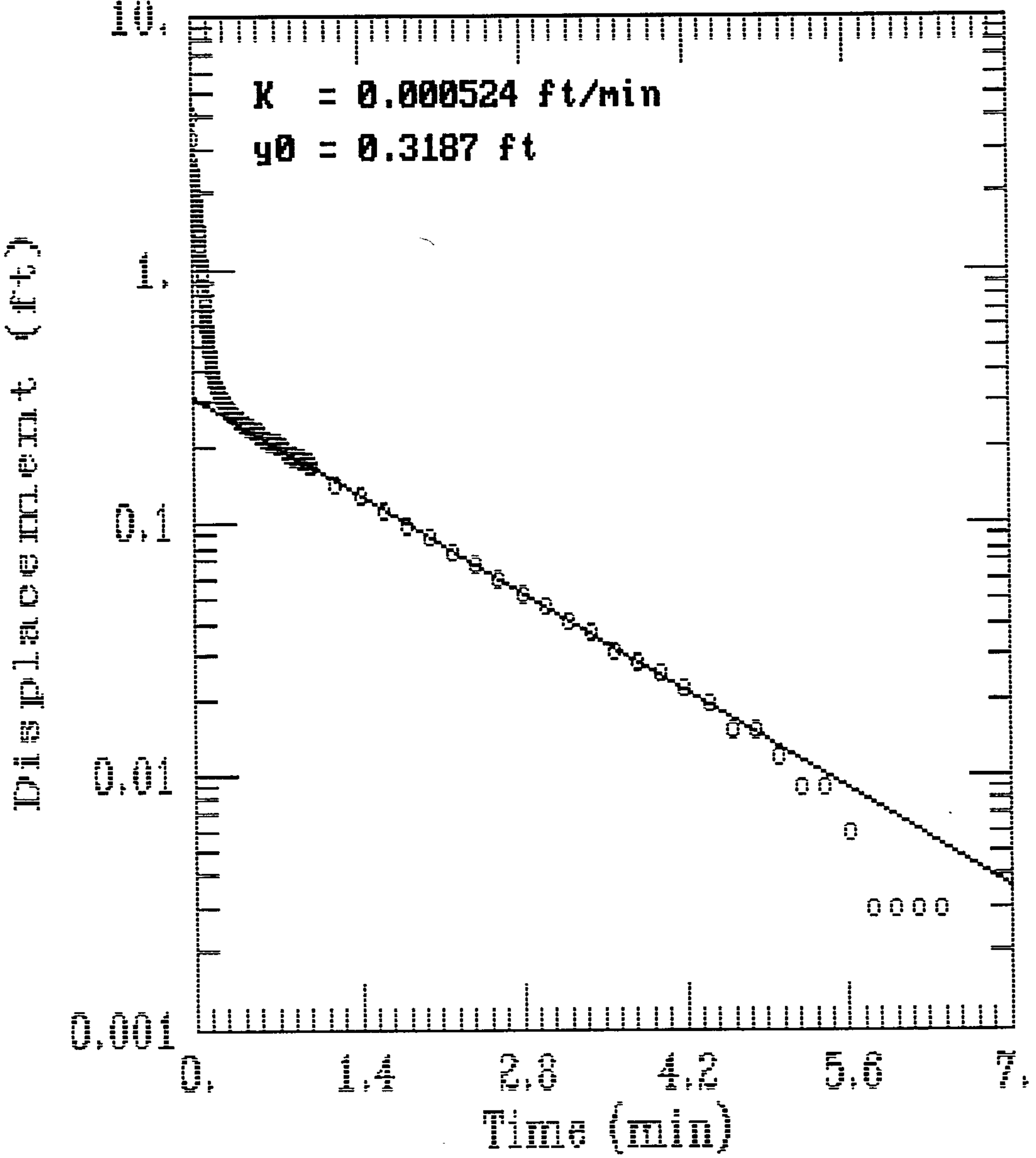
Ellsworth AFB MW34 - Rising - Quadratic



Ellsworth AFB MW35 - Falling

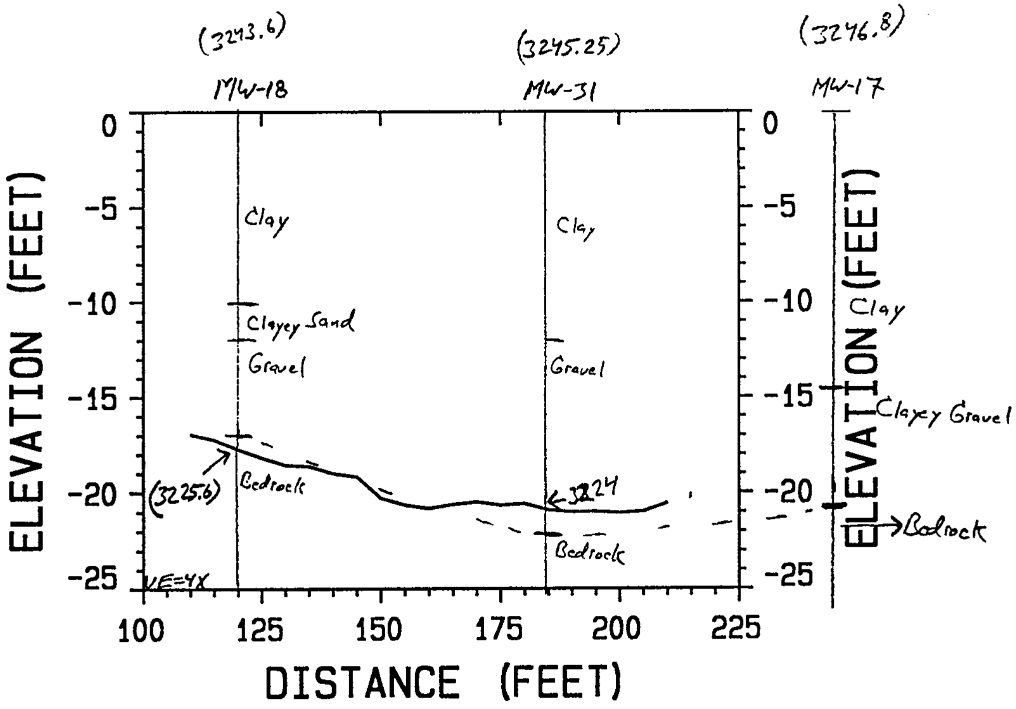


Ellsworth AFB MW35 - Rising

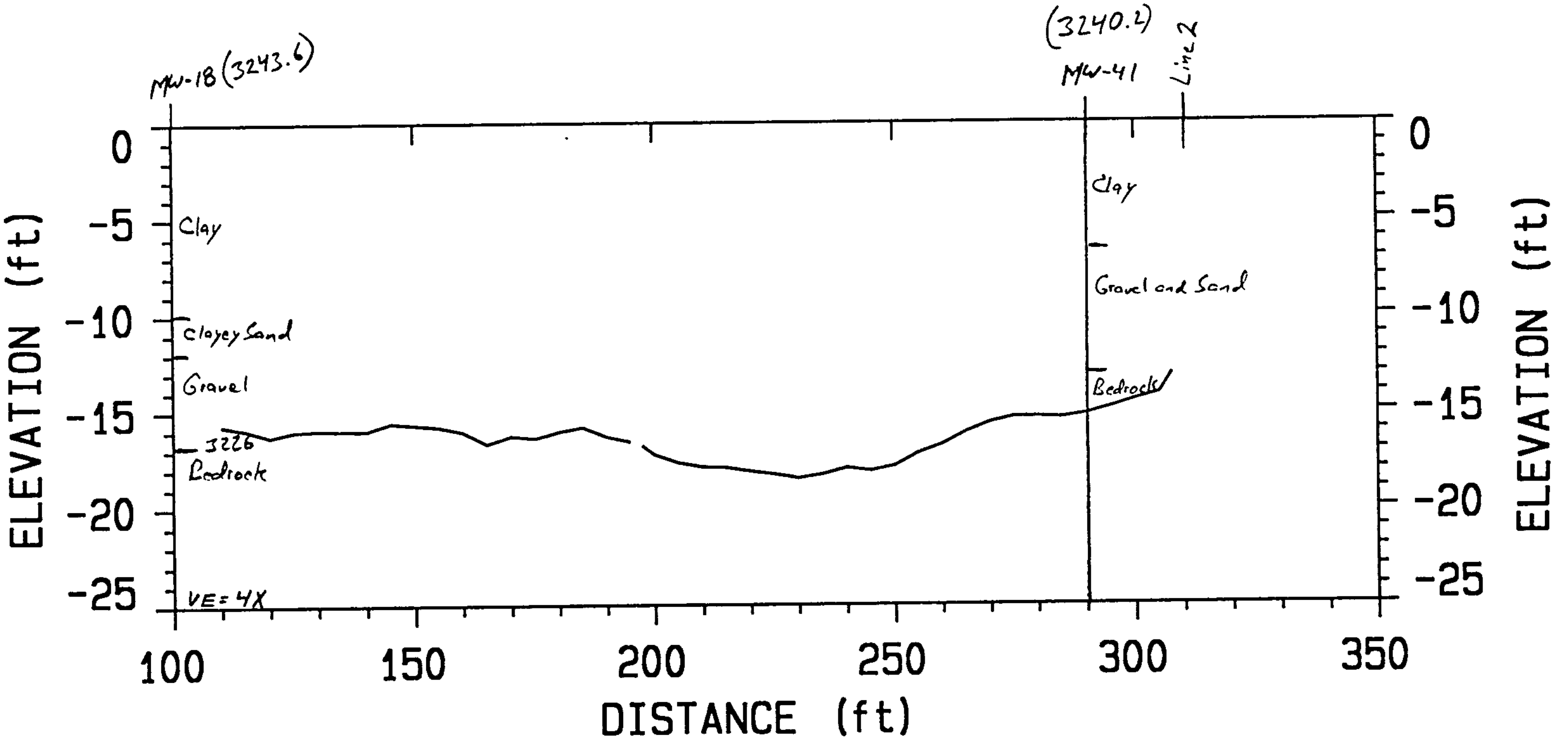


APPENDIX D

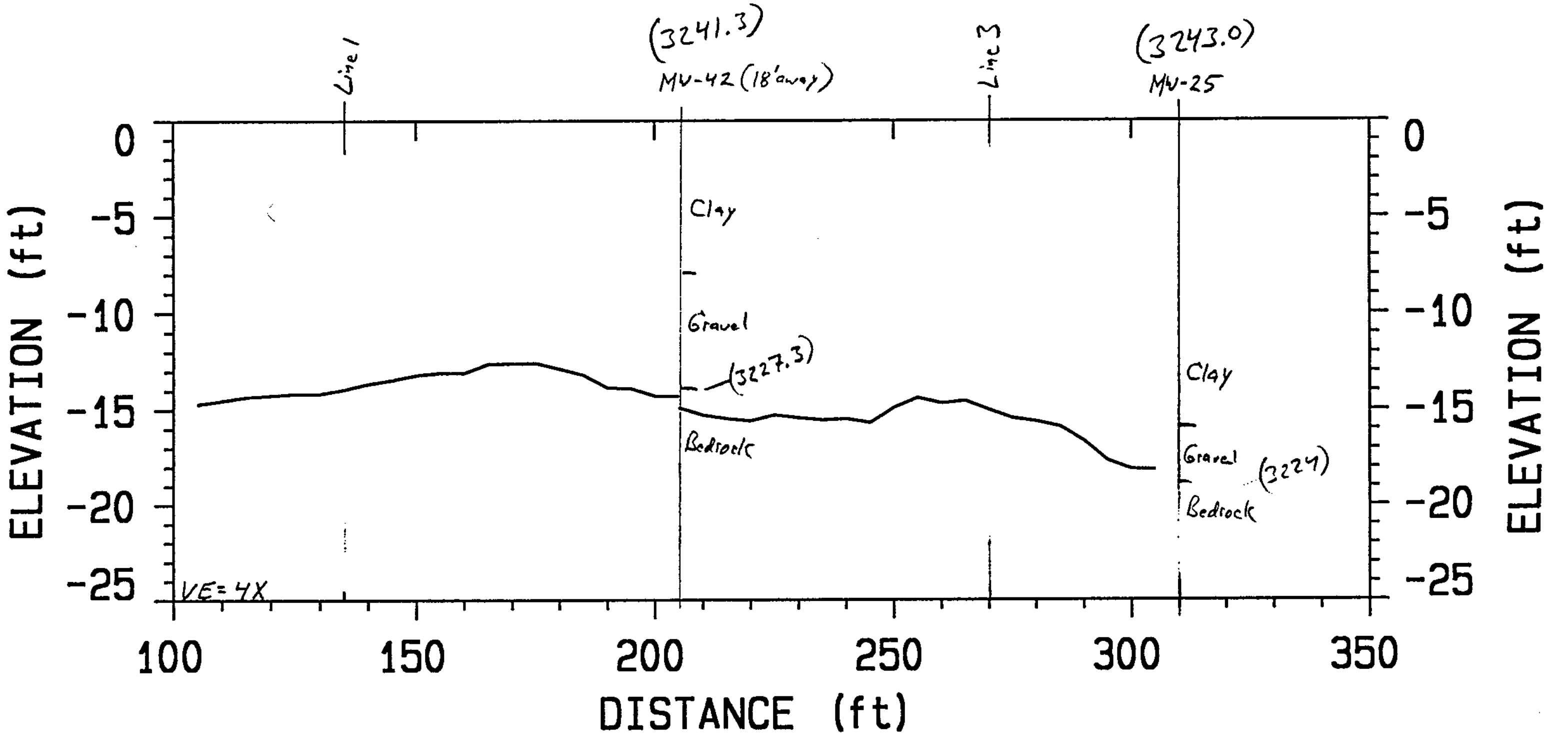
SEISMIC REFRACTION SURVEY RESULTS



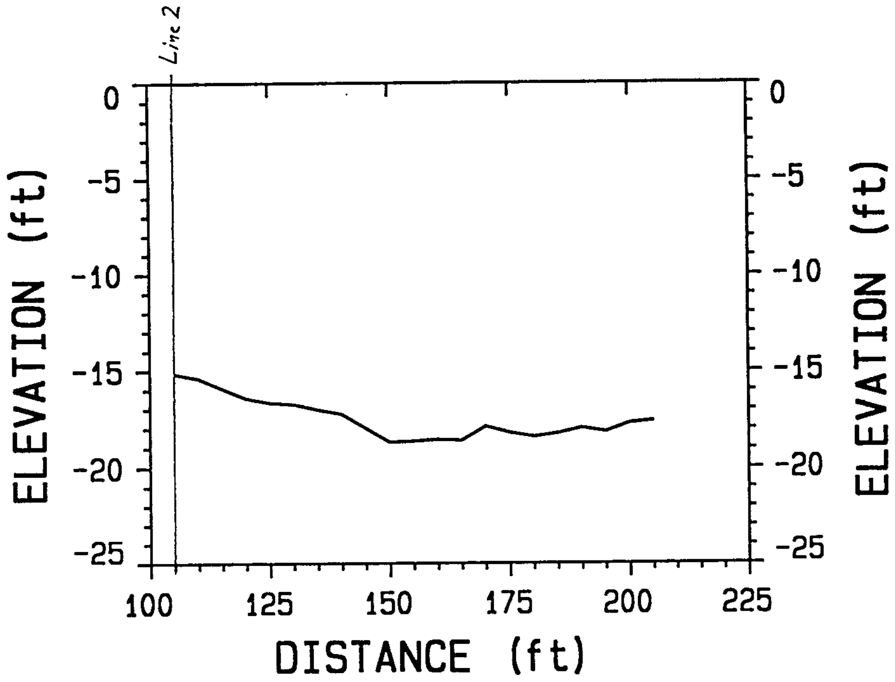
for: USAF	ELLSWORTH AFB
by: Parsons Engineering Science	TEST LINE (SHEAR WAVE)
Data Set TEST-2S · Date: 7/NOV/1994	
Equipment: EG&G GEOMETRIC · Spread: TEST	Azimuth:



for: USAF		ELLSWORTH AFB, SOUTH DAKOTA
by: Parsons Engineering Science		LINE 1
Data SetS-L1S2	Date: 11-8-94	
Equipment: GEOMETRICS R24	Spread: L1S2	Azimuth:



for: USAF		ELLSWORTH AFB, SOUTH DAKOTA
by: Parsons Engineering Science		LINE 2
Data SetS-L2S2	Date: 11-8-94	
Equipment: GEOMETRICS R24	Spread: L2S2	Azimuth:



for: USAF		ELLSWORTH AFB, SOUTH DAKOTA
by: Parsons Engineering Science		LINE 3
Data SetS-L3S1	Date: 11-8-94	
Equipment GEOMETRICS R24	Spread: L3S1	Azimuth:

APPENDIX E

RELEVANT GEOCHEMICAL DATA AND CONTAMIANT FATE AND TRANSPORT MODELS

THERMODYNAMIC DATA FOR FUELHYDROCARBON BIODEGRADATION REACTIONS

APPENDIX E

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

Electron Donor and Electron Acceptor Half Cell Reactions

HALF-CELL REACTIONS	ΔG°_r (kcal/ equiv)*	ΔG°_r (kJ/ equiv)*	E° (V)	Eh (V)	pe	Conditions for Eh and pe §
ELECTRON-ACCEPTOR (REDUCTION) HALF CELL REACTIONS						
$5e^- + 6H^+ + NO_3^- \Rightarrow 0.5N_2 + 3H_2O$ *Denitrification*	-28.7	-120.	+1.24	+0.708	+12.0	pH = 7 $\Sigma[N]=10^{-3}$
$4e^- + 4H^+ + O_2 \Rightarrow 2H_2O$ *Aerobic Respiration*	-28.3	-119.	+1.23	+0.805	+13.6	pH = 7 $P_{O_2}=0.21$ atm
$2e^- + 4H^+ + \underline{MnO_2} \Rightarrow Mn^{2+} + 2H_2O$ *Pyrolusite Dissolution/Reduction*	-28.3	-119	+1.23	+0.550	+9.27	pH = 7 $\Sigma[Mn]=10^{-5}$
$CO_2 + e^- + H^+ + \underline{MnOOH} \Rightarrow MnCO_3 + H_2O$ *a Manganite Carbonation/Reduction*	-23.1	-96.8	+1.00	+0.408	+6.90	pH = 8 $P_{CO_2}=10^{-2}$
$e^- + H^+ + MnO_2 \Rightarrow \underline{MnOOH}$ *Pyrolusite Hydrolysis/Reduction*	-22.1	-92.5	+0.959	+0.545	+9.21	pH = 7
$e^- + 3H^+ + \underline{Fe(OH)}_{3,amph.} \Rightarrow Fe^{2+} + 2H_2O$ *Amorphous "Goethite" Dissolution/Reduction*	-21.5	-89.9	+0.932	+0.163	+2.75	pH = 6 $\Sigma[Fe]=10^{-5}$
$8e^- + 10H^+ + NO^-_3 \Rightarrow NH^+_4 + 3H_2O$ *Nitrate Reduction*	-20.3	-84.9	+0.879	+0.362	+6.12	pH = 7
$2e^- + 2H^+ + NO^-_3 \Rightarrow NO^-_2 + H_2O$ *Nitrate Reduction*	-18.9	-78.9	+0.819	+0.404	+6.82	pH = 7
$e^- + 3H^+ + \underline{FeOOH} \Rightarrow Fe^{2+} + 2H_2O$ *"Ferric oxyhydroxide" Dissolution/Reduction*	-15.0	-62.9	+0.652	-0.118	-1.99	pH = 6 Σ $[Fe]=10^{-5}$
$e^- + 3H^+ + \underline{Fe(OH)}_{3,xline.} \Rightarrow Fe^{2+} + 3H_2O$ *Crystallized "Goethite" Dissolution/Reduction*	-11.8	-49.2	+0.510	-0.259	-4.38	pH = 6 Σ $[Fe]=10^{-5}$
$e^- + H^+ + CO_{2,g} + \underline{Fe(OH)}_{3,amph.} \Rightarrow \underline{FeCO_3} + 2H_2O$ *Amorphous "Goethite" Carbonation/Reduction*	-11.0	-46.2	+0.479	-0.113	-1.90	pH = 8 $P_{CO_2}=10^{-2}$ atm
$8e^- + 9H^+ + SO^{2-}_4 \Rightarrow HS^- + 4H_2O$ *Sulfate Reduction*	-5.74	-24.0	+0.249	-0.278	-4.70	pH = 8
$8e^- + 10H^+ + SO^{2-}_4 \Rightarrow H_2S^0 + 4H_2O$ *Sulfate Reduction*	-6.93	-28.9	+0.301	-0.143	-2.42	pH = 6
$C_2Cl_4 + H^+ + 2e^- \Rightarrow C_2HCl_3 + Cl^-$ *PCE Reductive Dechlorination*	-14.79	-61.9	+0.642	+0.553	+9.35	pH = 7 $[Cl-]=10^{-4}$
$C_2HCl_3 + H^+ + 2e^- \Rightarrow C_2H_2Cl_2 + Cl^-$ *TCE Reductive Dechlorination*	-14.50	-60.7	+0.629	+0.540	+9.13	pH = 7 $[Cl-]=10^{-4}$
$C_2H_2Cl_2 + H^+ + 2e^- \Rightarrow C_2H_3Cl + Cl^-$ *c-DCE Reductive Dechlorination*	-12.12	-50.7	+0.526	+0.437	+7.39	pH = 7 $[Cl-]=10^{-4}$
$C_2H_3Cl + H^+ + 2e^- \Rightarrow C_2H_4 + Cl^-$ *VC Reductive Dechlorination*	-13.73	-57.4	+0.595	+0.506	+8.55	pH = 7 $[Cl-]=10^{-4}$
$8e^- + 8H^+ + CO_{2,g} \Rightarrow CH_{4,g} + 2H_2O$ *Methanogenesis*	-3.91	-16.4	+0.169	-0.259	-4.39	pH = 7 $P_{CO_2}=10^{-2}$ $P_{CH_4}=10^0$

HALF-CELL REACTIONS	ΔG°_r (kcal/ equiv)*	ΔG°_r (kJ/ equiv)*	E° (V)	Eh (V)	pe	Conditions for Eh and pe §
ELECTRON-DONOR (OXIDATION) HALF CELL REACTIONS						
$12H_20 + C_6H_6 \Rightarrow 6CO_2 + 30H^+ + 30e^-$ *Benzene Oxidation*	+2.83	+11.8	-0.122	+0.316	+5.34	pH = 7 $P_{CO_2} = 10^{-2}$
$14H_20 + C_6H_5CH_3 \Rightarrow 7CO_2 + 36H^+ + 36e^-$ *Toluene Oxidation*	+2.96	+12.4	-0.128	+0.309	+5.22	pH = 7 $P_{CO_2} = 10^{-2}$
$16H_20 + C_6H_5C_2H_5 \Rightarrow 8CO_2 + 42H^+ + 42e^-$ *Ethylbenzene Oxidation*	+2.96	+12.4	-0.128	+0.309	+5.21	pH = 7 $P_{CO_2} = 10^{-2}$
$20H_2O + C_{10}H_8 \Rightarrow 10CO_2 + 48H^+ + 48e^-$ *Naphthalene Oxidation*	+2.98	+12.5	-0.130[a]	+0.309	+5.22	pH = 7 $P_{CO_2} = 10^{-2}$
$18H_2O + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 48H^+ + 48e^-$ *1,3,5-Trimethylbenzene Oxidation*	+3.07	+12.8	-0.133[a]	+0.303	+5.12	pH = 7 $P_{CO_2} = 10^{-2}$
$18H_2O + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 48H^+ + 48e^-$ *1,2,4-Trimethylbenzene Oxidation*	+3.07	+12.9	-0.134[a]	+0.302	+5.11	pH = 7 $P_{CO_2} = 10^{-2}$
$4H_2O + C_2H_3Cl \Rightarrow 2CO_2 + 11H^+ + 10e^- + Cl^-$ *Vinyl Chloride Oxidation*	-0.55	-2.30	+0.024[a]	-0.455	-7.69	pH = 7 $P_{CO_2} = 10^{-2}$
$12H_2O + C_6H_5Cl \Rightarrow 6CO_2 + 29H^+ + 28e^- + Cl^-$ *Chlorobenzene Oxidation*	+2.21	+9.26	-0.096[a]	+0.358	+6.05	pH = 7 $P_{CO_2} = 10^{-2}$

NOTES:

* = ΔG°_r for half cell reaction as shown divided by the number of electrons involved in reaction.

§ = Conditions assumed for the calculation of Eh and pe (pe = Eh/0.05916). Where two dissolved species are involved, other than those mentioned in this column, their activities are taken as equal. Note, this does not affect the free energy values listed.

[a] = E^0 calculated using the following equation; $E^0 = \Delta G^\circ_r (J/nF) * 1.0365 \times 10^{-5}$ (VF/J) from Stumm and Morgan, 1981

Coupled Oxidation Reactions

Coupled Benzene Oxidation Reactions	ΔG°$_r$ (kcal/mole Benzene)	ΔG°$_r$ (kJ/mole Benzene)	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$7.5 O_2 + C_6H_6 \Rightarrow 6 CO_{2,g} + 3 H_2O$ *Benzene oxidation /aerobic respiration*	-765.34	-3202	3.07:1
$6 NO_3^- + 6 H^+ + C_6H_6 \Rightarrow 6 CO_{2,g} + 6 H_2O + 3 N_{2,g}$ *Benzene oxidation / denitrification*	-775.75	-3245	4.77:1
$30 H^+ + 15\underline{MnO_2} + C_6H_6 \Rightarrow 6 CO_{2,g} + 15 Mn^{2+} + 18 H_2O$ *Benzene oxidation / manganese reduction*	-765.45	-3202	10.56:1
$3.75\ NO_3^- + C_6H_6 + 7.5\ H^+ + 0.75\ H_2O \Rightarrow 6\ CO_2 + 3.75\ NH_4^+$ *Benzene oxidation / nitrate reduction*	-524.1	-2193	2.98:1
$60 H^+ + 30\underline{Fe(OH)_{3,a}} + C_6H_6 \Rightarrow 6 CO_2 + 30 Fe^{2+} + 78 H_2O$ *Benzene oxidation / iron reduction*	-560.10	-2343	21.5:1
$7.5 H^+ + 3.75 SO_4^{2-} + C_6H_6 \Rightarrow 6 CO_{2,g} + 3.75 H_2S^o + 3H_2O$ *Benzene oxidation / sulfate reduction*	-122.93	-514.3	4.61:1
$4.5 H_2O + C_6H_6 \Rightarrow 2.25 CO_{2,g} + 3.75 CH_4$ *Benzene oxidation / methanogenesis*	-32.40	-135.6	0.77:1
$15C_2Cl_4 + 12H_2O + C_6H_6 \Rightarrow 15C_2HCl_3 + 6CO_2 + 15H^+ + 15Cl^-$ *Benzene oxidation/ Tetrachloroethylene reductive dehalogenation*	-358.59	-1500	31.8:1
$15C_2HCl_3 + 12H_2O + C_6H_6 \Rightarrow 15C_2H_2Cl_2 + 6CO_2 + 15H^+ + 15Cl^-$ *Benzene oxidation/ Trichloroethylene reductive dehalogenation*	-350.04	-1465	25.2:1
$15C_2H_2Cl_2 + 12H_2O + C_6H_6 \Rightarrow 15C_2H_3Cl + 6CO_2 + 15H^+ + 15Cl^-$ *Benzene oxidation/ cis-Dichloroethylene reductive dehalogenation*	-278.64	-1166	18.6:1
$15C_2H_3Cl + 12H_2O + C_6H_6 \Rightarrow 15C_2H_4 + 6CO_2 + 15H^+ + 15Cl^-$ *Benzene oxidation/ Vinyl chloride reductive dehalogenation*	-327.37	-1370	11.9:1

Coupled Toluene Oxidation Reactions	ΔG°$_r$ (kcal/mole Toluene)	ΔG°$_r$ (kJ/mole Toluene)	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$9 O_2 + C_6H_5CH_3 \Rightarrow 7 CO_{2,g} + 4 H_2O$ *Toluene oxidation /aerobic respiration*	-913.76	-3823	3.13:1
$7.2 NO_3^- + 7.2 H^+ + C_6H_5CH_3 \Rightarrow 7 CO_{2,g} + 7.6 H_2O + 3.6 N_{2,g}$ *Toluene oxidation / denitrification*	-926.31	-3875	4.85:1
$36 H^+ + 18\underline{MnO_2} + C_6H_5CH_3 \Rightarrow 7 CO_{2,g} + 18 Mn^{2+} + 22 H_2O$ *Toluene oxidation / manganese reduction*	-913.89	-3824	10.74:1
$72 H^+ + 36\underline{Fe(OH)_{3,a}} + C_6H_5CH_3 \Rightarrow 7 CO_2 + 36 Fe^{2+} + 94 H_2O$ *Toluene oxidation / iron reduction*	-667.21	-2792	21.86:1
$9 H^+ + 4.5 SO_4^{2-} + C_6H_5CH_3 \Rightarrow 7 CO_{2,g} + 4.5 H_2S^o + 4 H_2O$ *Toluene oxidation / sulfate reduction*	-142.86	-597.7	4.7:1
$5 H_2O + C_6H_5CH_3 \Rightarrow 2.5 CO_{2,g} + 4.5 CH_4$ *Toluene oxidation / methanogenesis*	-34.08	-142.6	0.78:1
$18C_2Cl_4 + 14H_2O + C_6H_5CH_3 \Rightarrow 18C_2HCl_3 + 7CO_2 + 18H^+ + 18Cl^-$ *Toluene oxidation/ Tetrachloroethylene reductive dehalogenation*	-425.66	-1781	32.4:1
$18C_2HCl_3 + 14H_2O + C_6H_5CH_3 \Rightarrow 18C_2H_2Cl_2 + 7CO_2 + 18H^+ + 18Cl^-$ *Toluene oxidation/ Trichloroethylene reductive dehalogenation*	-415.40	-1738	25.7:1
$18C_2H_2Cl_2 + 14H_2O + C_6H_5CH_3 \Rightarrow 18C_2H_3Cl + 7CO_2 + 18H^+ + 18Cl^-$ *Toluene oxidation/ cis-Dichloroethylene reductive dehalogenation*	-329.72	-1380	18.9:1
$18C_2H_3Cl + 14H_2O + C_6H_5CH_3 \Rightarrow 18C_2H_4 + 7CO_2 + 18H^+ + 18Cl^-$ *Toluene oxidation/ Vinyl chloride reductive dehalogenation*	-388.22	-1624	12.1:1

Coupled Ethylbenzene Oxidation reactions	ΔG°_r kcal/mole Ethylbenzene	ΔG°_r kJ/mole Ethylbenzene	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$10.5 O_2 + C_6H_5C_2H_5 \Rightarrow 8 CO_{2,g} + 5 H_2O$ *Ethylbenzene oxidation /aerobic respiration*	-1066.13	-4461	3.17:1
$8.4 NO_3^- + 8.4 H^+ + C_6H_5C_2H_5 \Rightarrow 8 CO_{2,g} + 9.2 H_2O + 4.2 N_{2,g}$ *Ethylbenzene oxidation / denitrification*	-1080.76	-4522	4.92:1
$46 H^+ + 22\underline{MnO_2} + C_6H_5C_2H_5 \Rightarrow 8 CO_{2,g} + 22 Mn^{2+} + 28 H_2O$ *Ethylbenzene oxidation / manganese reduction*	-1066.27	-4461	11.39:1
$84 H^+ + 42\underline{Fe(OH)_{3,a}} + C_6H_5C_2H_5 \Rightarrow 8 CO_2 + 42 Fe^{2+} + 110 H_2O$ *Ethylbenzene oxidation / iron reduction*	-778.48	-3257	22.0:1
$10.5 H^+ + 5.25 SO_4^{2-} + C_6H_5C_2H_5 \Rightarrow 8 CO_{2,g} + 5.25 H_2S^o + 5 H_2O$ *Ethylbenzene oxidation / sulfate reduction*	-166.75	-697.7	4.75:1
$5.5 H_2O + C_6H_5C_2H_5 \Rightarrow 2.75 CO_{2,g} + 5.25 CH_4$ *Ethylbenzene oxidation / methanogenesis*	-39.83	-166.7	0.79:1
$21C_2Cl_4 + 16H_2O + C_6H_5C_2H_5 \Rightarrow 21C_2HCl_3 + 8CO_2 + 21H^+ + 21Cl^-$ *Ethylbenzene oxidation/ Tetrachloroethylene reductive dehalogenation*	-496.67	-2078	32.8:1
$21C_2HCl_3 + 16H_2O + C_6H_5C_2H_5 \Rightarrow 21C_2H_2Cl_2 + 8CO_2 + 21H^+ + 21Cl^-$ *Ethylbenzene oxidation/ Trichloroethylene reductive dehalogenation*	-484.70	-2028	26.0:1
$21C_2H_2Cl_2 + 16H_2O + C_6H_5C_2H_5 \Rightarrow 21C_2H_3Cl + 8CO_2 + 21H^+ + 21Cl^-$ *Ethylbenzene oxidation/ cis-Dichloroethylene reductive dehalogenation*	-384.74	-1610	19.2:1
$21C_2H_3Cl + 16H_2O + C_6H_5C_2H_5 \Rightarrow 21C_2H_4 + 8CO_2 + 21H^+ + 21Cl^-$ *Ethylbenzene oxidation/ Vinyl chloride reductive dehalogenation*	-452.99	-1895	12.3:1

Coupled m-Xylene Oxidation Reactions	ΔG°_r (kcal/mole *m*-xylene)	ΔG°_r (kJ/mole *m*-xylene)	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$10.5 O_2 + C_6H_4(CH_3)_2 \Rightarrow 8 CO_{2,g} + 5 H_2O$ *m-Xylene oxidation /aerobic respiration*	-1063.25	-4448	3.17:1
$8.4 NO_3^- + 8.4 H^+ + C_6H_4(CH_3)_2 \Rightarrow 8 CO_{2,g} + 9.2 H_2O + 4.2 N_{2,g}$ *m-Xylene oxidation / denitrification*	-1077.81	-4509	4.92:1
$46 H^+ + 22\underline{MnO_2} + C_6H_4(CH_3)_2 \Rightarrow 8 CO_{2,g} + 22 Mn^{2+} + 28 H_2O$ *m-Xylene oxidation / manganese reduction*	-1063.39	-4449	11.39:1
$84 H^+ + 42\underline{Fe(OH)_{3,a}} + C_6H_4(CH_3)_2 \Rightarrow 8 CO_2 + 42 Fe^{2+} + 110 H_2O$ *m-Xylene oxidation / iron reduction*	-775.61	-3245	22:1
$10.5 H^+ + 5.25 SO_4^{2-} + C_6H_4(CH_3)_2 \Rightarrow 8 CO_{2,g} + 5.25 H_2S^o + 5 H_2O$ *m-Xylene oxidation / sulfate reduction*	-163.87	-685.6	4.75:1
$5.5 H_2O + C_6H_4(CH_3)_2 \Rightarrow 2.75 CO_{2,g} + 5.25 CH_4$ *m-Xylene oxidation / methanogenesis*	-36.95	-154.6	0.79:1[a/]
$21C_2Cl_4 + 16H_2O + C_6H_4(CH_3)_2 \Rightarrow 21C_2HCl_3 + 8CO_2 + 21H^+ + 21Cl^-$ *m-Xylene oxidation/ Tetrachloroethylene reductive dehalogenation*	-493.79	-2066	32.8:1
$21C_2HCl_3 + 16H_2O + C_6H_4(CH_3)_2 \Rightarrow 21C_2H_2Cl_2 + 8CO_2 + 21H^+ + 21Cl^-$ *m-Xylene oxidation/ Trichloroethylene reductive dehalogenation*	-481.82	-2016	26.0:1
$21C_2H_2Cl_2 + 16H_2O + C_6H_4(CH_3)_2 \Rightarrow 21C_2H_3Cl + 8CO_2 + 21H^+ + 21Cl^-$ *m-Xylene oxidation/ cis-Dichloroethylene reductive dehalogenation*	-381.86	-1598	19.2:1
$21C_2H_3Cl + 16H_2O + C_6H_4(CH_3)_2 \Rightarrow 21C_2H_4 + 8CO_2 + 21H^+ + 21Cl^-$ *m-Xylene oxidation/ Vinyl chloride reductive dehalogenation*	-450.11	-1883	12.3:1

Coupled Naphthalene Oxidation Reactions	ΔG°_r (kcal/mole naphthalene)	ΔG°_r (kJ/mole naphthalene)	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$12O_2 + C_{10}H_8 \Rightarrow 10CO_2 + 4H_2O$ *Naphthalene oxidation /aerobic respiration*	-1217.40	-5094	3.00:1
$9.6NO_3^- + 9.6H^+ + C_{10}H_8 \Rightarrow 10CO_2 + 8.8H_2O + 4.8N_{2,g}$ *Naphthalene oxidation / denitrification*	-1234.04	-5163	4.65:1
$24MnO_2 + 48H^+ + C_{10}H_8 \Rightarrow 10CO_2 + 24Mn^{2+} + 28H_2O$ *Naphthalene oxidation / manganese reduction*	-1217.57	-5094	16.31:1
$48Fe(OH)_{3,a} + 96H^+ + C_{10}H_8 \Rightarrow 10CO_2 + 48Fe^{2+} + 124H_2O$ *Naphthalene oxidation / iron reduction*	-932.64	-3902	40.13:1
$6SO_4^{2-} + 12H^+ + C_{10}H_8 \Rightarrow 10CO_2 + 6H_2S^o + 4H_2O$ *Naphthalene oxidation / sulfate reduction*	-196.98	-824.2	4.50:1
$8H_2O + C_{10}H_8 \Rightarrow 4CO_2 + 6CH_4$ *Naphthalene oxidation / methanogenesis*	-44.49	-186.1	1.13:1
$24C_2Cl_4 + 20H_2O + C_{10}H_8 \Rightarrow 24C_2HCl_3 + 10CO_2 + 24H^+ + 24Cl^-$ *Naphthalene oxidation/ Tetrachloroethylene reductive dehalogenation*	-566.59	-2371	31.1:1
$24C_2HCl_3 + 20H_2O + C_{10}H_8 \Rightarrow 24C_2H_2Cl_2 + 10CO_2 + 24H^+ + 24Cl^-$ *Naphthalene oxidation/ Trichloroethylene reductive dehalogenation*	-552.91	-2313	24.6:1
$24C_2H_2Cl_2 + 20H_2O + C_{10}H_8 \Rightarrow 24C_2H_3Cl + 10CO_2 + 24H^+ + 24Cl^-$ *Naphthalene oxidation/ cis-Dichloroethylene reductive dehalogenation*	-438.67	-1835	18.2:1
$24C_2H_3Cl + 20H_2O + C_{10}H_8 \Rightarrow 24C_2H_4 + 10CO_2 + 24H^+ + 24Cl^-$ *Naphthalene oxidation/ Vinyl chloride reductive dehalogenation*	-516.67	-2162	11.6:1

Coupled 1,3,5-Trimethylbenzene Oxidation Reactions	ΔG°_r (kcal/mole 1,3,5-TMB)	ΔG°_r (kJ/mole 1,3,5-TMB)	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$12O_2 + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 6H_2O$ *1,3,5-Trimethylbenzene oxidation /aerobic respiration*	-1213.29	-5076	3.20:1
$9.6NO_3^- + 9.6H^+ + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 10.8H_2O + 4.8N_{2,g}$ *1,3,5-Trimethylbenzene oxidation / denitrification*	-1229.93	-5146	4.96:1
$24MnO_2 + 48H^+ + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 30H_2O + 24Mn^{2+}$ *1,3,5-Trimethylbenzene oxidation / manganese reduction*	-1213.46	-5077	17.40:1
$48Fe(OH)_{3,a} + 96H^+ + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 48Fe^{2+} + 126H_2O$ *1,3,5-Trimethylbenzene oxidation / iron reduction*	-928.53	-3885	42.80:1
$6SO_4^{2-} + 12H^+ + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 6H_2O + 6H_2S^o$ *1,3,5-Trimethylbenzene oxidation / sulfate reduction*	-192.87	-807.0	4.80:1
$6H_2O + C_6H_3(CH_3)_3 \Rightarrow 3CO_2 + 6CH_4$ *1,3,5-Trimethylbenzene oxidation / methanogenesis*	-40.39	-169.0	0.90:1
$24C_2Cl_4 + 18H_2O + C_6H_3(CH_3)_3 \Rightarrow 24C_2HCl_3 + 9CO_2 + 24H^+ + 24Cl^-$ *1,3,5-Trimethylbenzene oxidation/ Tetrachloroethylene reductive dehalogenation*	-562.48	-2353	33.2:1
$24C_2HCl_3 + 18H_2O + C_6H_3(CH_3)_3 \Rightarrow 24C_2H_2Cl_2 + 9CO_2 + 24H^+ + 24Cl^-$ *1,3,5-Trimethylbenzene oxidation/ Trichloroethylene reductive dehalogenation*	-548.80	-2296	26.3:1
$24C_2H_2Cl_2 + 18H_2O + C_6H_3(CH_3)_3 \Rightarrow 24C_2H_3Cl + 9CO_2 + 24H^+ + 24Cl^-$ *1,3,5-Trimethylbenzene oxidation/ cis-Dichloroethylene reductive dehalogenation*	-434.56	-1818	19.4:1
$24C_2H_3Cl + 18H_2O + C_6H_3(CH_3)_3 \Rightarrow 24C_2H_4 + 9CO_2 + 24H^+ + 24Cl^-$ *1,3,5-Trimethylbenzene oxidation/ Vinyl chloride reductive dehalogenation*	-512.56	-2145	12.4:1

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Coupled 1,2,4-Trimethylbenzene Oxidation Reactions	ΔG°$_r$ (kcal/mole 1,2,4-TMB)	ΔG°$_r$ (kJ/mole 1,2,4-TMB)	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$12O_2 + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 6H_2O$ *1,2,4-Trimethylbenzene oxidation /aerobic respiration*	-1212.92	-5075	3.20:1
$9.6NO_3^- + 9.6H^+ + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 10.8H_2O + 4.8N_{2,g}$ *1,2,4-Trimethylbenzene oxidation / denitrification*	-1229.56	-5144	4.96:1
$24\underline{MnO_2} + 48H^+ + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 30H_2O + 24Mn^{2+}$ *1,2,4-Trimethylbenzene oxidation / manganese reduction*	-1213.09	-5076	17.4:1
$48\underline{Fe(OH)}_{3,a} + 96H^+ + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 48Fe^{2+} + 126H_2O$ *1,2,4-Trimethylbenzene oxidation / iron reduction*	-928.16	-3883	42.8:1
$6SO_4^{2-} + 12H^+ + C_6H_3(CH_3)_3 \Rightarrow 9CO_2 + 6H_2O + 6H_2S^o$ *1,2,4-Trimethylbenzene oxidation / sulfate reduction*	-192.50	-805.4	4.80:1
$6H_2O + C_6H_3(CH_3)_3 \Rightarrow 3CO_2 + 6CH_4$ *1,2,4-Trimethylbenzene oxidation / methanogenesis*	-40.02	-167.4	0.90:1
$24C_2Cl_4 + 18H_2O + C_6H_3(CH_3)_3 \Rightarrow 24C_2HCl_3 + 9CO_2 + 24H^+ + 24Cl^-$ *1,2,4-Trimethylbenzene oxidation/ Tetrachloroethylene reductive dehalogenation*	-562.11	-2352	33.2:1
$24C_2HCl_3 + 18H_2O + C_6H_3(CH_3)_3 \Rightarrow 24C_2H_2Cl_2 + 9CO_2 + 24H^+ + 24Cl^-$ *1,2,4-Trimethylbenzene oxidation/ Trichloroethylene reductive dehalogenation*	-548.43	-2295	26.3:1
$24C_2H_2Cl_2 + 18H_2O + C_6H_3(CH_3)_3 \Rightarrow 24C_2H_3Cl + 9CO_2 + 24H^+ + 24Cl^-$ *1,2,4-Trimethylbenzene oxidation/ cis-Dichloroethylene reductive dehalogenation*	-434.19	-1817	19.4:1
$24C_2H_3Cl + 18H_2O + C_6H_3(CH_3)_3 \Rightarrow 24C_2H_4 + 9CO_2 + 24H^+ + 24Cl^-$ *1,2,4-Trimethylbenzene oxidation/ Vinyl chloride reductive dehalogenation*	-512.19	-2143	12.4:1

Coupled Chlorobenzene Oxidation Reactions	ΔG°$_r$ (kcal/mole Chlorobenzene)	ΔG°$_r$ (kJ/mole Chlorobenzene)	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$7O_2 + C_6H_5Cl \Rightarrow 6CO_2 + H^+ + 2H_2O + Cl^-$ *Chlorobenzene oxidation /aerobic respiration*	-731.62	-3061	2.00:1
$5.6NO_3^- + 4.6H^+ + C_6H_5Cl \Rightarrow 6CO_2 + 4.8H_2O + 2.8N_{2,g} + Cl^-$ *Chlorobenzene oxidation / denitrification*	-741.33	-3102	3.10:1
$14\underline{MnO_2} + 27H^+ + C_6H_5Cl \Rightarrow 6CO_2 + 16H_2O + 14Mn^{2+} + Cl^-$ *Chlorobenzene oxidation / manganese reduction*	-731.72	-3062	10.9:1
$28\underline{Fe(OH)}_{3,a} + 55H^+ + C_6H_5Cl \Rightarrow 6CO_2 + 72H_2O + 28Fe^{2+} + Cl^-$ *Chlorobenzene oxidation / iron reduction*	-565.51	-2366	26.8:1
$3.5SO_4^{2-} + 6H^+ + C_6H_5Cl \Rightarrow 6CO_2 + 2H_2O + 3.5H_2S^o + Cl^-$ *Chlorobenzene oxidation / sulfate reduction*	-136.38	-570.6	3.00:1
$5H_2O + C_6H_5Cl \Rightarrow 2.5CO_2 + 3.5CH_4 + H^+ + Cl^-$ *Chlorobenzene oxidation / methanogenesis*	-47.43	-198.4	0.80:1
$14C_2Cl_4 + 12H_2O + C_6H_5Cl \Rightarrow 14C_2HCl_3 + 6CO_2 + 15H^+ + 15Cl^-$ *Chlorobenzene oxidation/ Tetrachloroethylene reductive dehalogenation*	-351.99	-1473	20.7:1
$14C_2HCl_3 + 12H_2O + C_6H_5Cl \Rightarrow 14C_2H_2Cl_2 + 6CO_2 + 15H^+ + 15Cl^-$ *Chlorobenzene oxidation/ Trichloroethylene reductive dehalogenation*	-344.01	-1439	16.4:1
$14C_2H_2Cl_2 + 12H_2O + C_6H_5Cl \Rightarrow 14C_2H_3Cl + 6CO_2 + 15H^+ + 15Cl^-$ *Chlorobenzene oxidation/ cis-Dichloroethylene reductive dehalogenation*	-277.37	-1161	12.1:1
$14C_2H_3Cl + 12H_2O + C_6H_5Cl \Rightarrow 14C_2H_4 + 6CO_2 + 15H^+ + 15Cl^-$ *Chlorobenzene oxidation/ Vinyl chloride reductive dehalogenation*	-322.87	-1351	7.75:1

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Coupled Vinyl Chloride Oxidation Reactions	ΔG°_r (kcal/mole vinyl chloride)	ΔG°_r (kJ/mole vinyl chloride)	Stoichiometric Mass Ratio of Electron Acceptor to Compound
$2.5O_2 + C_2H_3Cl \Rightarrow 2CO_2 + H_2O + H^+ + Cl^-$ *Vinyl Chloride oxidation /aerobic respiration*	-288.98	-1209	1.29:1
$2NO_3^- + H^+ C_2H_3Cl \Rightarrow 2CO_2 + 2H_2O + Cl^- + N_{2,g}$ *Vinyl Chloride oxidation / denitrification*	-292.44	-1224	2.00:1
$5\underline{MnO}_2 + 9H^+ + C_2H_3Cl \Rightarrow 2CO_2 + 6H_2O + 5Mn^{2+} + Cl^-$ *Vinyl Chloride oxidation / manganese reduction*	-289.01	-1209	7.02:1
$10\underline{Fe(OH)}_{3,a} + 19H^+ + C_6H_3(CH_3)_3 \Rightarrow 2CO_2 + 10Fe^{2+} + 26H_2O + Cl^-$ *Vinyl Chloride oxidation / iron reduction*	-229.65	-960.9	17.3:1
$1.25SO_4^{2-} + 1.5H^+ + C_2H_3Cl \Rightarrow 2CO_2 + H_2O + 1.25H_2S^o + Cl^-$ *Vinyl Chloride oxidation / sulfate reduction*	-76.40	-319.7	1.94:1
$1.5H_2O + C_2H_3Cl \Rightarrow .75CO_2 + 1.25CH_4 + H^+ + Cl^-$ *Vinyl Chloride oxidation / methanogenesis*	-44.62	-186.7	0.44:1
$5C_2Cl_4 + 4H_2O + C_2H_3Cl \Rightarrow 5C_2HCl_3 + 2CO_2 + 6H^+ + 6Cl^-$ *Vinyl Chloride oxidation/ Tetrachloroethylene reductive dehalogenation*	-153.39	-641.8	13.4:1
$5C_2HCl_3 + 4H_2O + C_2H_3Cl \Rightarrow 5C_2H_2Cl_2 + 2CO_2 + 6H^+ + 6Cl^-$ *Vinyl Chloride oxidation/ Trichloroethylene reductive dehalogenation*	-150.54	-629.9	10.6:1
$5C_2H_2Cl_2 + 4H_2O + C_2H_3Cl \Rightarrow 5C_2H_3Cl + 2CO_2 + 6H^+ + 6Cl^-$ *Vinyl Chloride oxidation/ cis-Dichloroethylene reductive dehalogenation*	-126.74	-530.3	7.82:1

Gibbs Free Energy of Formation for Species used in Half-Cell reactions and Coupled Oxidation-Reduction Reactions

Species	State	$\Delta G^{o}_{f,298.15}$ (kcal/mole)	Source
e^-	i	0	std
H^+	i	0	std
O_2	g	0	std
H_2O	l	-56.687	Dean (1972)
Carbon Species			
CO_2	g	-94.26	Dean (1972)
CH_2O, formalydehyde	aq	-31.02	Dean (1972)
C_6H_6, benzene	l	+29.72	Dean (1972)
CH_4, methane	g	-12.15	Dean (1972)
$C_6H_5CH_3$, toluene	l	+27.19	Dean (1972)
$C_6H_5C_2H_5$, ethylbenzene	l	+28.61	Dean (1972)
$C_6H_4(CH_3)_2$, o-xylene	l	+26.37	Dean (1972)
$C_6H_4(CH_3)_2$, m-xylene	l	+25.73	Dean (1972)
$C_6H_4(CH_3)_2$, p-xylene	l	+26.31	Dean (1972)
C_2Cl_4, PCE	l	+1.1	CRC Handbook (1990)
C_2HCl_3, TCE	l	+2.9	CRC Handbook (1990)
$C_2H_2Cl_2$, c-DCE	l	+5.27	CRC Handbook (1990)
C_2H_4, ethene	g	+16.28	CRC Handbook (1990)
$C_{10}H_8$, naphthalene	l	+48.05	Dean (1972)
$C_6H_3(CH_3)_3$, 1,3,5-TMB	l	+24.83	Dean (1972)
$C_6H_3(CH_3)_3$, 1,2,4-TMB	l	+24.46	Dean (1972)
C_2H_3Cl, vinyl chloride	g	+12.4	Dean (1972)
C_6H_5Cl, chlorobenzene	l	+21.32	Dean (1972)
$C_{14}H_{10}$, phenanthrene	l	+64.12	Dean (1972)
Nitrogen Species			
NO_3^-	i	-26.61	Dean (1972)
N_2	g	0	std
NO_2^-	i	-7.7	Dean (1972)
NH_4^+	aq	-18.97	Dean (1972)
Sulfur Species			
SO_4^{2-}	i	-177.97	Dean (1972)
H_2S	aq	-6.66	Dean (1972)
H_2S	g	-7.9	Dean (1972)
HS^-	i	+2.88	Dean (1972)
Iron Species			
Fe^{2+}	i	-18.85	Dean (1972)
Fe^{3+}	i	-1.1	Dean (1972)
Fe_2O_3, hematite	c	-177.4	Dean (1972)
FeOOH, ferric oxyhydroxide	c	-117.2	Naumov *et al.* (1974)
$Fe(OH)_3$, goethite	a	-167.416	Langmuir and Whittemore (1971)
$Fe(OH)_3$, goethite	c	-177.148	Langmuir and Whittemore (1971)
$FeCO_3$, siderite	c	-159.35	Dean (1972)
Manganese Species			
Mn^{2+}	i	-54.5	Dean (1972)
MnO_2, pyrolusite	c	-111.18	Stumm and Morgan (1981)
MnOOH, manganite	c	-133.29	Stumm and Morgan (1981)
$MnCO_3$, rhodochrosite	p	-194	Dean (1972)
Chloride Species			
Cl^-	aq	-31.37	Dean (1972)

NOTES:

c = crystallized solid
a = amorphous solid (may be partially crystallized - dependent on methods of preparation)
p = freshly precipitated solid
i = dissociated, aqueous ionic species (concentration = 1 m)
aq = undissociated aqueous species
g = gaseous
l = liquid
std = accepted by convention
Wherever possible multiple sources were consulted to eliminate the possibility of typographical error.

SESOIL MODEL BACKGROUND, INPUT VALUES, AND RESULTS

CCC-629

OAK RIDGE NATIONAL LABORATORY

managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY

RSIC COMPUTER CODE COLLECTION

SESOIL

Code System to Calculate One-Dimensional Vertical Transport for the Unsaturated Soil Zone

Contributed by

Oak Ridge National Laboratory
Oak Ridge, Tennessee
and
Wisconsin Department of Natural Resources
Madison, Wisconsin

RADIATION SHIELDING INFORMATION CENTER

The New SESOIL User's Guide

(Revision 1.6)
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Prepared by:

Stephen J. Scott: President
Environmental Graphics Inc.
N18W27620 Lakefield Drive
Pewaukee, WI 53072
414-691-7413

&

David M. Hetrick: SESOIL Consultant
8417 Mecklenburg CT
Knoxville TN 37923
615-576-7556

Designed for

Carol McCurry: Project Manager
&
Michael J. Barden: Technical Manager

Wisconsin Department of Natural Resources
Emergency & Remedial Response Section
Bureau of Solid & Hazardous Waste Management
101 South Webster Street
Madison, WI 53707

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Kenneth J. Ladwig: Principle Investigator
Science & Technology Management, Inc.
2511 North 124th Street
Brookfield, WI 53005
414-785-5952

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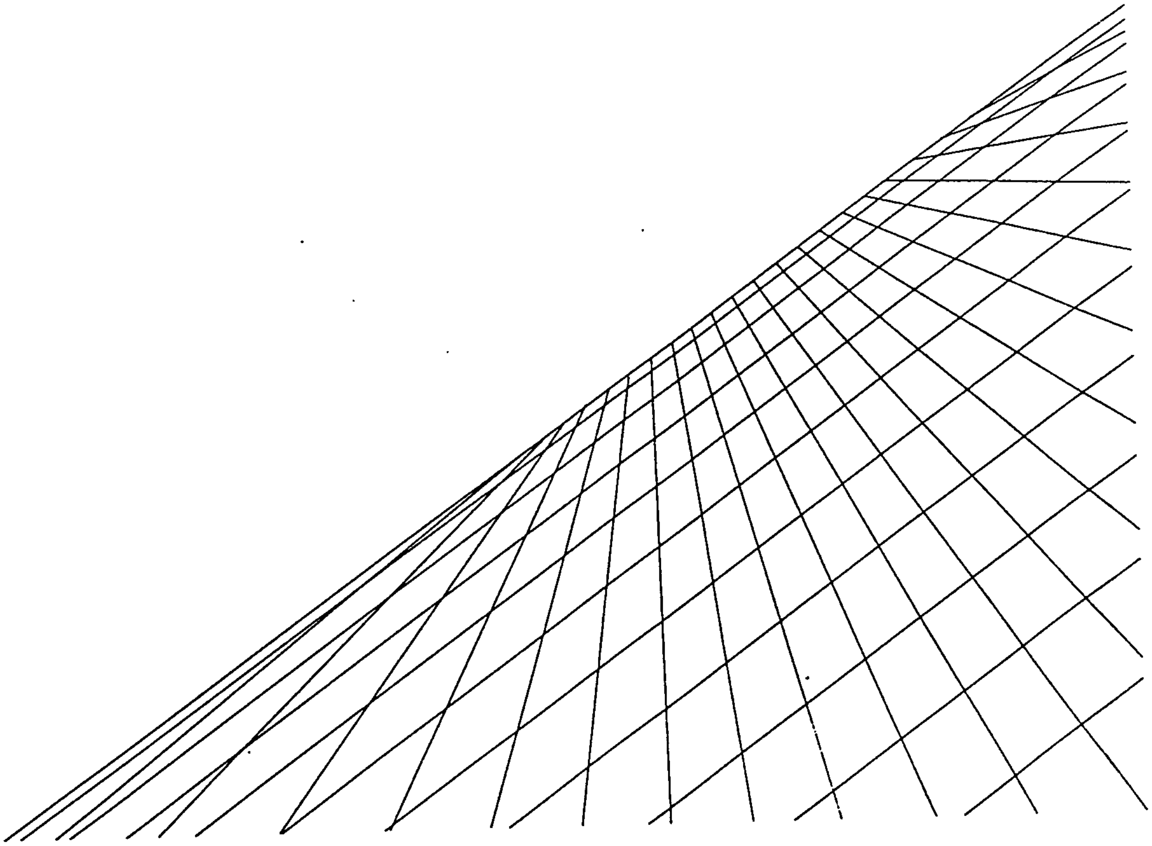
David M. Hetrick
Stephen J. Scott
with Michael. J. Barden



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Introduction Overview of the SESOIL Model

1

SESOIL is an acronym for Seasonal Soil Compartment Model and is a one-dimensional vertical transport code for the unsaturated soil zone. It is an integrated screening-level soil compartment model and is designed to simultaneously model water transport, sediment transport, and pollutant fate. The program was developed for EPA's Office of Water and the Office of Toxic Substances (OTS) in 1981 by Arthur D. Little, Inc. (ADL). ADL updated the SESOIL model in 1984 to include a fourth soil compartment (the original model included up to three layers) and the soil erosion algorithms (Bonazountas and Wagner, 1984). A comprehensive evaluation of SESOIL performed by Watson and Brown (1985) uncovered numerous deficiencies in the model, and subsequently, SESOIL was modified extensively by Hetrick et al. at Oak Ridge National Laboratory (ORNL) to enhance its capabilities (see Hetrick et al., 1986, 1988, 1989). The model is designed to be self-standing, but SESOIL was incorporated into a system called PCGEMS (Graphical Exposure Modeling System for the PC), a complete information management tool developed for EPA-OTS and designed to help users perform exposure assessments (General Sciences Corporation, 1987, 1989). Subsequently, PCGEMS was turned into the system called RISKPRO, which has numerous additions and improvements to PCGEMS, and is fully supported (General Sciences Corporation, 1990). The purpose of this document is to provide an up-to-date users manual for SESOIL as it is used in the RISKPRO system.

☐ ***Side Note:*** *The SESOIL program is written in the FORTRAN language.*

SESOIL was developed as a screening-level model, utilizing less soil, chemical, and meteorological values as input than most other similar models. Output of the SESOIL model includes time-varying pollutant concentrations at various soil depths and pollutant loss from the unsaturated zone in terms of surface runoff, percolation to the groundwater, volatilization, and degradation.

The SESOIL model accepts time-varying pollutant loading. For example, it is able to simulate chemical releases to soil from a variety of sources such as landfill disposal, accidental leaks, agricultural applications, leaking underground storage tanks, or deposition from the atmosphere. Other potential applications of SESOIL include long term leaching studies from waste disposal sites, pesticide and sediment transport on watersheds, studies of hydrologic cycles and water balances of soil compartments, and precalibration runs for other simulation models, One may also run the model to estimate the effect of various site management or design strategies on pollutant distributions and concentrations in the environment.

SESOIL can be used as a screening tool in performing exposure assessments. OTS used the model to predict the behavior of pollutants in soil compartments for analyzing and prioritizing chemical exposures. A number of studies have been conducted on the SESOIL model including sensitivity analysis, comparison with other models, and comparisons with field data (Bonazountas et al., 1982; Wagner et al., 1983; Hetrick, 1984; Kincaid et al., 1984; Watson and Brown, 1985; Hetrick et al., 1986; Melancon et al., 1986; Hetrick et al., 1988; Hetrick et al., 1989). SESOIL has been applied in risk assessments concerning direct coal liquefaction (Walsh et al., 1984), incineration of hazardous waste (Holton et al., 1985; Travis et al., 1986), the transport of benzene to groundwater (Tucker et al., 1986), to soil cleanup levels in California (Odencrantz et al., 1991, 1992), and to site sensitivity ranking for Wisconsin soils for the Wisconsin Department of Natural Resources (Ladwig et al., 1992).

The soil column in SESOIL is a user-defined compartment extending from the surface through the unsaturated zone to the groundwater table. Typically, SESOIL is used to estimate the rate of migration of chemicals through soils and the concentration of the chemical in soil layers following chemical release to the soil environment. SESOIL's simulation of chemical persistence considers mobility, volatility, and degradation. The model performs calculations on an annual or monthly basis, and can simulate up to 99 years of chemical transport.

The model requires several types of chemical- and site-specific data to estimate the concentration of the chemical in the soil, its rate of leaching toward groundwater, and the impact of other environmental pathways. The user is required to provide chemical properties and release rate, and soil and climate data. This user's guide is designed to provide users of SESOIL with the information needed to efficiently and appropriately run the model and interpret the results. It provides a brief overview of how SESOIL can be used as an assessment tool. This document discusses the assumptions and equations used in the model and describes the use of SESOIL in the RISKPRO system, including details on how to build the input data files. A complete discussion of the output data file from SESOIL and the graphing capabilities available in the RISKPRO system is provided.

1.1 The RISKPRO System

The RISKPRO system simplifies data input by providing interactive prompts, parameter menus, and data retrieval programs in order for the user to extract pertinent data from on-line databases, create the input files required by SESOIL, run the model, and review and graph the model results.

The minimum system requirements for RISKPRO are:

- IBM XT/AT/PS2, 80386 or compatibles with 640 K RAM
- Hard Disk and 1 floppy disk drive
- DOS Version 2.2 or higher
- Graphics display adapter
- 540 K RAM available at all times
- 8087, 80287, or 80387 Math Co-processor.

☐ ***Side Note:*** *Although the math co-processor is not required, it is highly recommended since it substantially reduces computer time.*

SESOIL Model Description

3

SESOIL is a one-dimensional vertical transport model for the unsaturated soil zone. SESOIL can consider only one compound at a time and the model is based on mass balance and equilibrium partitioning of the chemical between different phases (dissolved, sorbed, vapor, and pure). The SESOIL model was designed to perform long-term simulations of chemical transport and transformations in the soil. The model uses theoretically derived equations to represent water transport, sediment transport on the land surface, pollutant transformation, and migration of the pollutant to the atmosphere and groundwater. Climatic data, compartment geometry, and soil and chemical property data are the major components used in the equations.

The expression "long term" applies to both annual and monthly simulations in SESOIL, and is used in contrast to "short-term" models which employ a storm-by-storm resolution. Some soil models are designed to estimate pollutant distribution in the soil after each major storm event, and simulate chemical concentrations in the soil on a daily basis (e.g., see Patterson et al., 1984). These models are data intensive, requiring, for example, hourly rainfall input and daily maximum and minimum temperatures. SESOIL, on the other hand, estimates pollutant distribution in the soil column and on the watershed after a "season", which can be defined by the user as a year or a month. This is accomplished using a statistical water balance analysis and a washload routine statistically driven within the season. This approach saves time for the model user by reducing the amount of data that must be provided, and also reduces computer time and resource requirements since fewer computations are required.

☐ ***Side Note:***
The SESOIL model is not data intensive.

Two operation options are available for running SESOIL: annual estimates (Option A) requiring annual climatic data, and monthly estimates (Option M) requiring monthly data. It is recommended that the monthly option always be selected as it will provide a better estimate of chemical movement through the soil. RISKPRO simplifies the task of compiling monthly input data by extracting pertinent data from on-line databases (see the next section on building input data files using RISKPRO). Thus, the monthly option is no more difficult to use than the annual option. Option A is not available in the RISKPRO system, and this option will not be discussed further in this report with the exception of the hydrologic cycle, which implements the annual algorithm as described below. The annual option has not been changed from the original model, and those users interested in the annual option are referred to the report by Bonazountas and Wagner (1984).

The processes modeled by SESOIL are categorized into three cycles: hydrology, sediment, and pollutant transport. Each cycle is a separate sub-model within the SESOIL code. Most mathematical environmental simulation models may be categorized as stochastic or deterministic models. Both the stochastic and deterministic models are theoretically derived. Stochastic models incorporate the concept of probability or some other measure of uncertainty, while deterministic models describe the system in terms of cause/effect relationships. SESOIL employs a stochastic approach for the hydrologic and washload cycles, and a deterministic approach for the pollutant transport cycle.

3.1 The Soil Compartment

In SESOIL, the soil compartment (or column) is a cell extending from the surface through the unsaturated zone to the upper level of the saturated soil zone, also referred to as the aquifer or groundwater table. While SESOIL estimates the pollutant mass added to the groundwater, the saturated zone is not modeled. The output from SESOIL can be used for generating input values for groundwater transport models. (In RISKPRO, the Analytic Transient 1-2-3 Dimensional Model, AT123D (Yeh, 1981), has been adapted to use SESOIL results for groundwater runoff (recharge) to simulate chemical movement in the saturated zone.)

☐ *Side Note:*
Two to four layers and up to 40 sublayers, 10 in each layer, can be specified.

The soil compartment is treated differently by the hydrologic cycle and the pollutant cycle in SESOIL. In the hydrologic cycle, the whole soil column is treated as a single homogeneous compartment extending from the land surface to the water table. The pollutant cycle breaks the soil column into several compartments, also called layers. The layers in the pollutant cycle can be further broken up into sublayers. Each soil layer (sublayer) is considered as a compartment with a set volume and the total soil column is treated as a series of interconnected layers (sublayers). Each layer (sublayer) can receive and release pollutant to and from adjacent layers (sublayers).

The dimensions of the soil compartment are defined by the user. The width and length of the column are defined as the area of application of pollutant released to the soil, and the depth to the groundwater is determined from the thickness of user-defined soil layers that are used in the pollutant cycle. The soil column can be represented in 2, 3, or 4 distinct layers. Up to 10 sublayers can be specified for each layer, each having the same soil properties as the layer in which they reside.

There is no optimal size for the soil layers (sublayers); the dimensions of the soil column can be specified to cover any area from one square centimeter to several square kilometers. The area of the compartments is important for mass balance, but in terms of pollutant concentration the area of application is irrelevant since it is constant for all layers (sublayers). Note that the equations in SESOIL have been normalized to an area of one square centimeter.

It is suggested that the minimum depth of a layer is one centimeter. Depending on the application, layer depths can range from a shallow root zone of 5-25 centimeters, to a deep layer of more than 10 meters. When the pollutant enters a layer (sublayer), the model assumes instantaneous and uniform distribution of the chemical throughout that layer (sublayer). The model performs mass balance calculations over each entire soil layer (sublayer); there is no concentration gradient within a layer (sublayer). For a given amount of chemical released, the larger the layer (sublayer), the lower the calculated chemical concentration. For this reason, SESOIL was discretized to allow as many as ten sublayers in each of the four possible major layers. Thus, the user may define as many as 40 smaller compartments using these sublayers. The result is an increase in the resolution of the model.

3.2 SESOIL Cycles

Pollutant transport and transformation in the unsaturated soil zone are complex processes affected by chemical, soil, and hydrogeological properties. In SESOIL, these processes are included in one of three cycles: the hydrologic cycle to deal with moisture movement or flow through the compartment, the sediment or washload cycle to deal with runoff from the soil surface, and the pollutant fate cycle. SESOIL was developed by integrating three submodels, one to deal with each cycle. The specific processes associated with each cycle are accounted for in the submodels. The cycles and their associated processes are summarized in Table 3.1 and Diagram 1 shows a schematic of the soil column.

The hydrologic cycle is done first in SESOIL, followed by the sediment cycle, and these results are used in the pollutant fate cycle. The hydrologic cycle is based on a statistical, dynamic formulation of a vertical water budget. It has been adapted to account for either yearly or monthly simulations and for moisture variations in the soil. The hydrologic cycle controls the sediment cycle, which is a theoretical monthly washload routine. The pollutant cycle simulates transport and transformation processes in three phases present in the soil compartment: soil-air or gaseous phase, soil-moisture phase, and adsorbed or soil-solids phase. The three major cycles are summarized in the sections that follow.

Table 3.1
SESOIL CYCLES

Hydrologic Cycle

- Rainfall
- Groundwater runoff (recharge)
- Capillary rise
- Soil moisture retention (storage)
- Infiltration
- Surface runoff
- Evapotranspiration

Sediment Cycle

- Sediment washload (erosion due to storms)

Pollutant Fate Cycle

- Advection
- Diffusion (air phase)
- Sorption
- Washload
- Groundwater runoff (recharge)
- Chemical degradation/decay
- Cation exchange
- Volatilization
- Hydrolysis
- Surface runoff
- Metal complexation

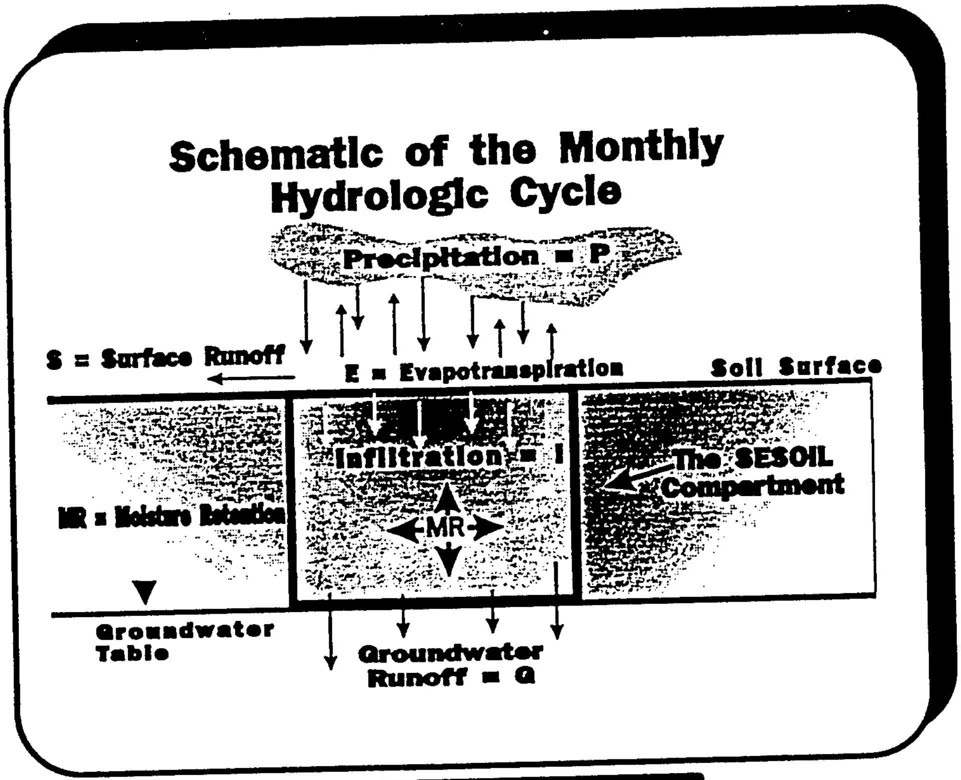

Schematic of the Monthly Hydrologic Cycle
Precipitation = P
S = Surface Runoff
E = Evapotranspiration
Soil Surface
Infiltration = I
The SESOIL Compartment
MR = Moisture Retention
MR
Groundwater Table
Groundwater Runoff = G

Diagram 1

3.3 Hydrologic Cycle

The hydrologic cycle is one-dimensional, considers vertical movement only, and focuses on the role of soil moisture (or interstitial pore water) in the soil compartment. The hydrologic cycle submodel calculates results for the hydrology of a site and passes these results to both the sediment washload cycle and the pollutant fate cycle. The hydrologic cycle used in SESOIL is an adaptation of the water balance dynamics theory of Eagleson (1978). The theory can be described as a dimensionless analytical representation of an annual water balance. It is itself a model based on simplified models of interacting hydraulic processes, including terms for the climate, soil, and vegetation. These processes are coupled through statistically based modeling.

It is beyond the scope of this manual to present the detailed physics and mathematical expressions of the model. The hydrologic cycle is thoroughly described by Eagleson (1978) and summarized by Bonazountas and Wagner (1984), and is based on the water balance equations shown below. All of these parameters are expected or mean annual values, and in SESOIL they are expressed in centimeters.

$$P - E - MR = S + G = Y \qquad (1)$$

$$I = P - S \qquad (2)$$

where:

P = precipitation
E = evapotranspiration
MR = moisture retention
S = surface runoff
I = infiltration
Y = yield
G = groundwater runoff or recharge (includes term for capillary rise)

Briefly, precipitation is represented by Poisson arrivals of rectangular gamma-distributed intensity pulses that have random depth and duration. Infiltration is described by the Philip equation (Philip, 1969), which assumes the medium to be effectively semi-infinite, and the internal soil moisture content at the beginning of each storm and inter-storm period to be uniform at its long-term average. Percolation to the groundwater is assumed to be steady throughout each time step of simulation, at a rate determined by the long-term average soil moisture content. Capillary rise from the water table is assumed to be steady throughout the time period and to take place to a dry surface. The work of Penman (1963), Van den Honert (1948), and Cowan (1965) is employed in calculating evapotranspiration (Eagleson, 1978). Surface runoff is derived from the distribution of rainfall intensity and duration, and by use of the Philip infiltration equation. The effects of moisture storage are included in the monthly option in SESOIL, based on the work of Metzger and Eagleson (1980).

Eagleson's theory assumes a one-dimensional vertical analysis in which all processes are stationary in the long-term average. The expression "long term" applies to both annual and monthly simulations in SESOIL, and is used in contrast to "short-term" models which employ a storm-by-storm resolution. Also, Eagleson's approach assumes that the soils are homogeneous and that the soil column is semi-infinite in relation to the surface processes. Thus, in the hydrologic cycle of SESOIL, the entire unsaturated soil zone is conceptualized as a single layer (or compartment) and the prediction for soil water content is an average value for the entire unsaturated zone.

While the user can provide different permeability values as input for each of the four major soil layers for the pollutant cycle in SESOIL, the hydrologic cycle will compute and use the depth-weighted average permeability according to the formula:

$$K_z = \frac{d}{\sum_{i=1}^{n} \frac{d_i}{K_i}} \qquad (3)$$

where:

K_z = vertically averaged permeability (cm^2),
K_i = permeability for layer i (cm^2),
d = depth from surface to groundwater (cm),
d_i = thickness of layer i (cm).

Thus, the user should exercise care when applying SESOIL to sites with large vertical variations in soil properties. The average permeability calculated by Eq. (3) in the hydrologic cycle may not be what the user intended and the resulting computed average soil moisture content may not be valid.

There is no explicit consideration of snow and ice, which are entered as precipitation. The model assumes that the water table elevation is constant with no change in groundwater storage from year to year. Bonazountas et al. (1984) adopted this theory for both annual and monthly simulations.

Each process in Eqs. (1) and (2) is written in terms of the soil moisture content, and solution of the equations is accomplished by iterating on soil moisture until the calculated value for precipitation is within 1.0% of the measured value input by the user. When this iteration is complete, the components such as infiltration, evapotranspiration, etc., in Eqs. (1) and (2) are known. SESOIL uses this procedure in both the annual and monthly routines. The monthly routine is an extension of the annual routine; both are discussed further below.

3.3.1 Annual Cycle

The annual water balance routine is based on Eagleson's (1978) theory. It encompasses one year, so multiple years have to be simulated as separate cycles. This routine simply determines the soil moisture content based on solution to equations (1) and (2) using annual climatic parameters. When the value for soil moisture content is arrived at through the iteration technique, the various processes described in equations (1) and (2) are known. Note that storage effects in the soil are not considered in the annual option. The theoretical basis for the annual dynamic hydrologic cycle used in SESOIL has been validated by Eagleson (1978). Annual model predictions were compared with empirical observations for five years of precipitation data at both a subhumid and arid climate location, with close agreement.

3.3.2 Monthly Cycle

The monthly water balance routine is based on the same theory as the annual routine, with modifications made to the details of moisture transfer from month-to-month (handling of moisture storage), and the radiation effects. The initial value for soil moisture content is calculated in SESOIL by summing the appropriate monthly climatic input data (for the first year) to obtain annual values and using the annual cycle algorithm. Then for each month, the monthly input values for precipitation, mean storm number, and mean length of the rain season are multiplied by 12 in order to again obtain "annual" values. Equations (1) and (2) are solved to compute the soil moisture content, and the results for the components (infiltration, evapotranspiration, etc.) are divided by 12 to attain average monthly values.

Note that if long-term average climatic data are used as input for each year (input for each month is the same from year to year), one would expect that the results for the hydrology for each month would be identical from year to year.

However, since the initial soil moisture content is computed as stated above for the first month (of the first year), this value will be different than the soil moisture calculated for the twelfth month that is then used for the first month of the following year. Thus, although hydrology results will not be identical for the first two years, they will be identical thereafter.

The monthly cycle in SESOIL does account for the change in moisture storage from month to month, incorporating the work of Metzger and Eagleson (1980). Also, the SESOIL evapotranspiration algorithm has been modified from the original work of Eagleson (1978) to include seasonal changes in average monthly radiation (radiation was a constant function of latitude before). Hetrick (1984) observed that hydrology predictions of the original SESOIL were insensitive to seasonal changes in meteorological data. To model the hydrology more realistically, an algorithm from the AGTEHM model (Hetrick et al., 1982) which computes daily potential radiation (incoming radiation for cloudless skies) for a given latitude and Julian date (December 31 = 365) is now used. The middle day of the month is used in the algorithm and the effect of cloud cover is calculated with the expression (Hetrick et al., 1982):

$$\bar{S} = S[(1-C) + kC] \qquad (4)$$

where:

$\bar{S}$ = the average monthly radiation,

S = the potential radiation,

C = the fraction of sky covered by clouds, and

k = the transmission factor of cloud cover.

The value for k used in the model is 0.32, suggested by Hetrick et al. (1982). Since latitude and monthly cloud cover are required input for SESOIL, no new input data are needed to support this modification. There are now more pronounced monthly changes in evapotranspiration predictions (see Hetrick et al., 1986).

Although SESOIL does produce monthly results for soil moisture content of the root zone, defined in the model as the first 100 cm depth from the surface, this option has not been fully developed. Thus, values for soil moisture for the root zone will usually be identical to those for the entire soil column, and only very dry climates may cause a difference (M. Bonazountas, personal communication, 1986).

SESOIL model predictions (using the monthly option) of watershed hydrologic components have been compared with those of the more data intensive terrestrial ecosystem hydrology model AGTEHM (Hetrick et al., 1982) as well as to empirical measurements at a deciduous forest watershed and a grassland watershed (see Hetrick et al., 1986). Although there were some differences in monthly results between the two models, good agreement was obtained between model predictions for annual values of infiltration, evapotranspiration, surface runoff, and groundwater runoff (recharge). Also, SESOIL model predictions compared well with the empirical measurements at the forest stand and the grassland watersheds.

3.3.3 Hydrologic Model Calibration

Calibration of unsaturated soil zone models can be uncertain and difficult because climate, soil moisture, soil infiltration and percolation are strongly interrelated parameters that are difficult and expensive to measure in the field. However, if at all possible, input parameters for any unsaturated soil zone model should be calibrated so that hydrologic predictions agree with observations. In SESOIL, all input parameters required for the hydrologic cycle can be estimated from field studies with the exception of the pore disconnectedness index, "c". This parameter is defined as the exponent relating the "wetting" or "drying" time-dependent permeability of a soil to its saturated permeability (Eagleson, 1978; Eagleson and Tellers, 1982). Brooks and Corey (1966) presented the following relationship:

$$K(S) = K(1)S^{c} \qquad (5)$$

where:

$K(1)$ = saturated hydraulic conductivity (cm/s),

$K(S)$ = hydraulic conductivity at S (cm/s),

S = percent saturation,

c = pore disconnectedness index.

Thus, this parameter is not commonly found in the literature. Default values for c suggested by Eagleson (1978) and Bonazountas and Wagner (1981, 1984) are: clay 12; silty clay loam 10; clay loam 7.5; silt loam 5.5; sandy loam 6; sandy clay loam 4; and sand 3.7. However, when data are available, this parameter should be varied first to optimize agreement between SESOIL results and hydrologic measurements. It should be noted that most unsaturated soil zone models require detailed data (which are difficult to obtain), such as soil moisture characteristic curves. The "one variable" approach of Eagleson (1978) simplifies the data estimation process and reduces computational time.

Other sensitive parameters for the hydrologic cycle are the effective porosity and the intrinsic permeability (e.g., see Hetrick et al., 1986, 1989). While other parameters can be varied when calibrating the model to measured hydrologic data, it is recommended that the user vary the disconnectedness index first, followed by the permeability and/or porosity. See the section on input data for further details.

3.4 Sediment Washload Cycle

In pollutant transport models, estimates of erosion and sediment yield on watersheds may be needed in order to compute the removal of sorbed chemicals on eroded sediments. A major factor in this process is the surface runoff, rainwater which does not infiltrate the soil and may carry dissolved pollutant. Surface runoff is computed as part of the hydrologic cycle. Erosion is a function of the rate of surface runoff and several other factors. These factors include the impact of raindrops which detaches soil particles and keeps them in motion as overland flow, surface features such as vegetation and roughness, and infiltration capacity. Because of the difficulty in directly measuring washload using water quality monitoring techniques, estimation techniques and models are widely employed.

The sediment cycle of SESOIL is optional; it can be turned on or off by the user. Thus, if pollutant surface runoff is considered negligible, the washload cycle can be neglected. If the option is used, SESOIL employs EROS, a theoretical sediment yield model (Foster et al., 1980), which is part of the CREAMS model (Knisel, 1980; Foster et al., 1980). The erosion component considers the basic processes of soil detachment, transport, and deposition. The EROS model uses separate theoretically derived equations for soil detachment and sediment transport. Separate equations are needed for these two processes because the relationship of the detachment process to erosion is different than the relationship between erosion and transport.

For the detachment process, the model employs the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), modified by Foster et al. (1980) for single storm events. The USLE is applicable for predictions of annual sediment erosion originating mainly from small watersheds which are subject to sheet and rill erosion. Detachment of soil particles occurs when the sediment load already in the overland flow is less than the sediment capacity of this flow. The equation takes into account soil erodibility (the rate of soil loss per storm), which varies for different soil types and texture classes. The USLE considers topography, since both the length and the steepness of the land slope affect the rate of rain-induced soil erosion. Also, the land cover (e.g. vegetation) and the roughness of the soil surface affect the rate of erosion and the rate of overland transport. The USLE includes a parameter called "Manning's n", or roughness coefficient, to model these influences.

To model the sediment transport capacity for overland flow, EROS incorporates the Yalin Transport Equation (Yalin, 1963), modified for nonuniform sediment with a mixture of particle sizes and densities. The model estimates the distribution of sediment particles transported as sand, silt, and clay, and the fraction of organic matter in the eroded sediment. SESOIL computations of sediment transport are performed for each particle size type, beginning at the upper end of a slope and routing sediment downslope.

The EROS model in SESOIL accounts for several surface features which may divert and slow the overland flow, allowing settling and deposition of the washload. These include vegetation, which slows the flow and filters out particles, and topography, which includes surface characteristics such as roughness and the existence of small depressions. Change in slope and loss of water through infiltration into the soil will reduce the flow rate and encourage settling of soil particles. Organic matter is distributed among the particle types based on the proportion of primary clay in each type (Foster et al., 1980). Soil receiving the deposited sediment is referred to as enriched. EROS computes sediment enrichment based on the ratio of the surface area of the sediment and organic matter to that of the surface area of the residual soil (Knisel et al., 1983).

3.4.1 Implementation In SESOIL

The EROS model uses characteristic rainfall and runoff factors for a storm to compute erosion and sediment transport for that storm (Foster et al., 1980). Hydrologic input to the erosion component consists of rainfall volume, rainfall erosivity, runoff volume, and the peak rate of runoff for each storm event. These terms drive soil detachment and subsequent transport by overland flow. Note that input data for the hydrologic cycle of SESOIL include total monthly precipitation, the number of storms per month, and the mean time of each rainfall event. Since SESOIL provides only monthly estimates of hydrologic parameters and in order to couple the SESOIL and EROS models, a statistical method is used to generate the amount of rainfall and duration of each storm for every rainfall event during the month. This algorithm employs a model featuring probability distributions in order to estimate the individual storm parameters (Eagleson, 1978; Grayman and Eagleson, 1969).

The washload cycle has been implemented with two subroutines in addition to the EROS, model PARAM and STORM, which take the input data for and results generated by the hydrologic cycle and adapt them for use. The PARAM subroutine supports EROS by first retrieving the hydrologic input data (e.g. the number of storm events per month and the depth of rainfall) read by SESOIL and then setting specific parameters applicable to the STORM and EROS subroutines. The STORM subroutine then uses the PARAM results and statistically generates information about each storm using the algorithm mentioned above. Thus, the coupled SESOIL/EROS model does not require any additional hydrologic input parameters for individual storms. However, it should be recognized that estimates of rainfall for each storm may be quite different than the actual values.

Additional data needed for the sediment cycle include the washload area, the fraction of sand, silt and clay in the soil, the average slope and slope length of the representative overland flow profile, the soil erodibility factor, the soil loss ratio, the contouring factor, and Manning's n coefficient for soil cover and surface roughness. Example values for these parameters can be found in the CREAMS documentation (Knisel, 1980; Foster et al., 1980). Note that the washload area should be less than or equal to the pollutant application area.

EROS takes the information generated by both the PARAM and STORM subroutines and computes estimates of the sediment yield for each month. Information from the sediment cycle, along with information from the hydrologic cycle, is then provided to the pollutant fate cycle, which will be discussed in the next subsection.

The coupled SESOIL/EROS model was evaluated by comparing predictions to published measured data (Hetrick and Travis, 1988). Two cornfield watersheds and one grassland watershed were included in the study. The sites differed in their management practices, soil type, ground cover, and meteorology. The model predictions were in fair to good agreement with observed data from the three watersheds, except for months where surface runoff came from one or two high intensity storms (Hetrick and Travis, 1988).

3.5 Pollutant Fate Cycle

The pollutant fate cycle focuses on the various chemical transport and transformation processes which may occur in the soil. These processes are summarized in Table 3.1, and are discussed in more detail in the subsections that follow. The pollutant fate cycle uses calculated results from the hydrologic cycle and the sediment washload cycle. Information from these cycles is automatically provided to the pollutant fate cycle.

In SESOIL, the ultimate fate and distribution of the pollutant is controlled by the processes interrelated by the mass balance equation (6) below. The processes are selectively employed and combined by the pollutant fate cycle based on the chemical properties and the simulation scenario specified by the user. The actual quantity or mass of pollutant taking part in any one process depends on the competition among all the processes for available pollutant mass. Pollutant availability for participation in these processes, and the pollutant rate of migration to the groundwater, depends on its partitioning in the soil between the gas (soil air), dissolved (soil moisture), and solid (adsorbed to soil) phases.

3.5.1 Foundation

In SESOIL, any layer (sublayer) can receive pollutant, store it, and export it to other subcompartments. Downward movement of pollutant occurs only with the soil moisture, while upward movement can occur only by vapor phase diffusion. Like the hydrologic cycle, the pollutant fate cycle is based on a mass balance equation (Eq. 6) that tracks the pollutant as it moves in the soil moisture between subcompartments. Upon reaching and entering a layer or sublayer, the model assumes instantaneous uniform distribution of the pollutant throughout that layer or sublayer. The mass balance equation is:

$$O(t-1)+I(t)=T(t)+R(t)+M(t) \qquad (6)$$

where:

$O(t-1)$ = the amount of pollutant originally in the soil compartment at time t-1 ($\mu g/cm^2$),

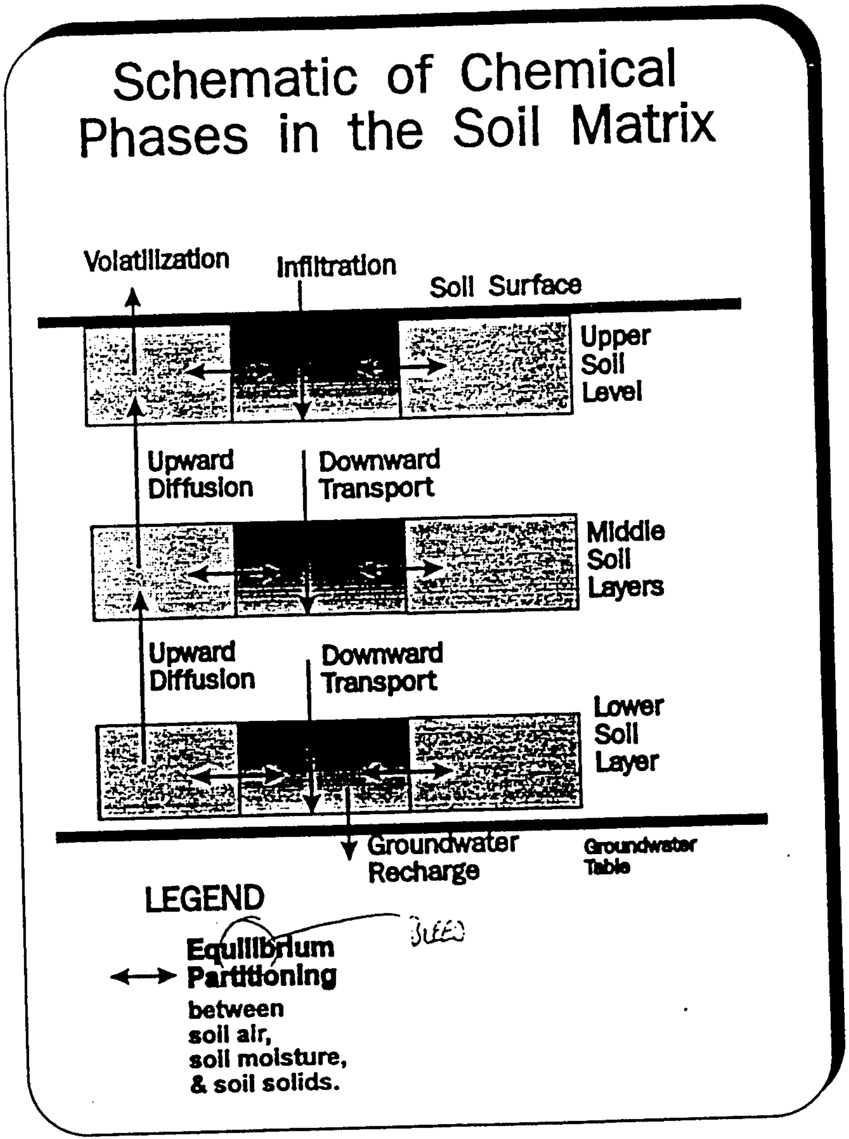
$I(t)$ = the amount of pollutant entering the soil compartment during a time step ($\mu g/cm^2$),

$T(t)$ = the amount of pollutant transformed within the soil compartment during the time step ($\mu g/cm^2$),

$R(t)$ = the amount of pollutant remaining in the soil compartment at time t ($\mu g/cm^2$),

$M(t)$ = the amount of pollutant migrating out of the soil compartment during the time step ($\mu g/cm^2$).

The fate of the pollutant in the soil column includes both transport and transformation processes, which depend on the chemical's partitioning among the three phases: soil air, soil moisture, and soil solids. The three phases are assumed to be in equilibrium with each other at all times (see Diagram 2), and the partitioning is a function of user-supplied chemical-specific partition coefficients and rate constants. Once the concentration in one phase is known, the concentrations in the other phases can be calculated. The pollutant cycle of SESOIL is based on the chemical concentration in the soil water. That is, all the processes are written in terms of the pollutant concentration in soil water and the model iterates on the soil moisture concentration until the system defined by Eq. (6) balances.



Schematic of Chemical Phases in the Soil Matrix

DIAGRAM 2

The concentration in the soil air is calculated via the modified Henry's law:

$$c_{sa} = \frac{cH}{R(T+273)} \qquad (7)$$

where:

c_{sa} = pollutant concentration in soil air (µg/mL),

c = pollutant concentration in soil water (µg/mL),

H = Henry's law constant (m^3 atm/mol),

R = gas constant [$8.2 * 10^{-5}$ m^3atm/(mol ^oK)], and

T = soil temperature (^oC).

The concentration adsorbed to the soil is calculated using the Freundlich isotherm (note that a cation exchange option, discussed later, is available in SESOIL).

$$s = K_d c^{\frac{1}{n}} \qquad (8)$$

where:

s = pollutant adsorbed concentration (µg/g),

K_d = pollutant partitioning coefficient (µg/g)/(µg/mL),

c = pollutant concentration in soil water (µg/mL), and

n = Freundlich exponent.

The total concentration of the pollutant in the soil is computed as:

$$c_o = f_a \bullet c_{sa} + \theta \bullet c + \rho_b s \qquad (9)$$

where:

c_o = overall (total) pollutant concentration (µg/cm^3),

f_a = f - θ= the air-filled porosity (mL/mL),

f = soil porosity (mL/mL),

θ = soil water content (mL/mL), and

ρ_b = soil bulk density (g/cm^3).

In SESOIL, each soil layer (sublayer) has a set volume and the total soil column is treated as a series of interconnected layers. Each layer (sublayer) has its own mass balance equation [Eq. (6)] and can receive and release pollutant to and from adjacent layers (sublayers). Again, the individual fate processes that compose the SESOIL mass balance equations (e.g., volatilization, degradation) are functions of the pollutant concentration in the soil water of each zone and a variety of first-order rate constants, partitioning coefficients, and other constants. An iterative solution procedure is used to solve the system (the iteration parameter is **c**). See Bonazountas and Wagner (1984) for the numerical solution procedure.

The pollutant cycle equations are formulated on a monthly basis and results are given for each month simulated. However, to account for the dynamic processes in the model more accurately, an explicit time step of 1 day is used in the equations. The monthly output represents the summation of results from each day.

In the event that the dissolved concentration exceeds the aqueous solubility of the pollutant, the dissolved concentration is assumed to equal the aqueous solubility. That is, if during solution of the mass balance equation for any one layer, the dissolved concentration exceeds the solubility of the chemical, the iteration is stopped for that time step and the solubility is used as the dissolved concentration. The adsorbed and soil-air concentrations are calculated using the chemical partitioning equations as before [Eqs. (7) and (8)]. To maintain the mass balance, the remaining pollutant is assumed to remain in a pure phase (undissolved). Transport of the pure phase is not considered, but the mass of the chemical in the pure phase is used as input to that same layer in the next time step. Simulation continues until the pure phase eventually disappears. The pure phase capability was not part of the original model and was added to SESOIL by Hetrick et al. (1989).

The discussion in the subsections that follow introduces the user to major algorithms and processes simulated in the pollutant cycle of SESOIL.

3.5.2 The Pollutant Depth Algorithm

The pollutant cycle in SESOIL is based on the pollutant concentration in soil moisture. In theory, a non-reactive dissolved pollutant originating in any unsaturated soil layer will travel to another soil layer or to the groundwater at the same speed as the moisture mass originating in the same soil layer. The movement of a reactive pollutant however, will be retarded in relation to the movement of the bulk moisture mass due to vapor phase partitioning and the adsorption of the pollutant on the soil particles. If it is assumed that no adsorption occurs, and the vapor phase is negligible, the pollutant will move at the same rate as water through the soil.

Originally, only the advective velocity was used in SESOIL to determine the depth the pollutant reached during a time step. The depth (D) was calculated as

$$D = \frac{J_w t_c}{\theta} \qquad (10)$$

where:

J_w = water velocity (cm/s),

t_c = advection time (s), and

θ = soil water content (cm^3/cm^3).

This approach allows all chemicals to reach the groundwater at the same time, irrespective of their chemical sorption characteristics. To account for retardation, SESOIL now uses the following equation to calculate the depth reached by a chemical with a linear equilibrium partitioning between its vapor, liquid, and adsorbed phases (Jury et al., 1984):

$$D = \frac{J_w t_c}{\theta + \rho_b K_d + \frac{f_a H}{R\,(T+273)}} \qquad (11)$$

SESOIL calculates the flux J_w for each layer using the infiltration rate and groundwater runoff (recharge) rate computed by the hydrologic cycle, and the depths and permeabilities input by the user. Note that a different permeability can be input for each of the four major soil layers. While the hydrologic cycle will use the weighted mean average of layer permeabilities according to Eq. (3), the pollutant cycle does take into account the separate permeability for each layer in computing J_w at the layer boundaries according to the following equation:

$$J_{w,z} = [G + (I - G)(\frac{d_j}{d})](\frac{k_i}{K_z}) \qquad (12)$$

where:

$J_{w,z}$ = infiltration rate at depth z, which will be the boundary between two major layers (cm/s),

G = groundwater runoff (recharge) (cm/s),

I = infiltration at surface (cm/s),

d_j = depth of soil column below depth z (cm),

d = depth of soil column from surface to groundwater table (cm),

K_z = intrinsic permeability defined by Eq. (3)cm^2), and

k_i = the vertically-averaged permeability for layer i (cm^2); is computed using Eq. (3) except d in the numerator of Eq. (3) is the sum of the layer depths above depth z and the summation in the denominator is from layer 1 to layer i.

The user is allowed two options for loading of pollutant: (1) a spill loading where all the pollutant is entered at the soil surface in the first time step of the month when the loading takes place, or (2) a steady application where the pollutant load is distributed evenly for each time step during the month at which the loading is specified. Option (1) allows loading at the soil surface only (layer 1, sublayer 1), whereas option (2) will allow loading in one or more of the four major layers. If sublayers are specified, the loading will always be entered into the first (top) sublayer of the major layer. Thus, while pollutant can be loaded in each of the four major layers, pollutant can not be loaded into each sublayer of a major layer to get a specific initial concentration distribution for the major layer.

If there is a spill loading or if the pollutant is entered as a steady application in layer 1 (sublayer 1), then the depth of the pollutant front is calculated using Eq. (11) starting from the surface. If a steady loading is specified in layers 2, 3, and/or 4, then the depth of the pollutant front is assumed to begin at the **middle** of the lowest layer at which pollutant is loaded (sublayer 1 of that layer if sublayers are included) and Eq. (11) is used to compute the depth of the pollutant front from that point. Subsequently, the pollutant is not allowed to enter a layer/sublayer until the depth of the pollutant front has reached the top of that layer/sublayer. When the pollutant depth reaches the groundwater table, pollutant leaves the unsaturated zone by simply multiplying the groundwater runoff (recharge) rate by the concentration in the soil moisture.

☐ ***Side Note:*** *Although a spill loading can not be used in SESOIL for layers 2, 3, or 4, an initial soil-sorbed concentration can still be approximated for these layers. See Section 4.5 for more information and Appendix A contains an example.*

3.5.3 Volatilization/Diffusion

In SESOIL, volatilization/diffusion includes movement of the pollutant from the soil surface to the atmosphere and from lower soil layers to upper ones. Note that vapor phase diffusion in SESOIL operates in the upward direction only. The rate of diffusion for a chemical is determined by the properties of the chemical, the soil properties, and environmental conditions. The volatilization/diffusion model in SESOIL is based on the model of Farmer et al. (1980) and Millington and Quirk (1961) and is a discretized version of Fick's first law over space, assuming vapor phase diffusion as the rate controlling process. That is, the same equation is used for volatilization to the atmosphere as is used for diffusion from lower layers to upper ones. The vapor phase diffusion flux through the soil J_a ($\mu g/cm^2 s$) is described as

$$J_a = -D_a \left(\frac{f_a^{\frac{10}{3}}}{f^2} \right) \frac{dC_{sa}}{dz} \qquad (13)$$

where:

D_a = the vapor diffusion coefficient of the compound in air (cm^2/s), and

c_{sa} = comes from Eq. (7) and f and f_a are as defined previously.

The volatilization algorithm in the original version of SESOIL allowed pollutant in the second (or lower) layer to volatilize directly to the atmosphere. This algorithm was modified by Hetrick et al. (1989). The pollutant can volatilize directly to the atmosphere from the surface layer, but if the chemical is in the second or lower layer, and the concentration in that layer is greater than the layer above it, then the chemical will diffuse into the upper layer rather than volatilize directly into the atmosphere.

An option the user has in the volatilization algorithm is to "turn off" the calculation by use of an input index parameter (for each layer). For example, if the index is set to 0.0 for each layer, the pollutant would not be allowed to diffuse upward or volatilize to the atmosphere; only downward movement of the pollutant with the soil moisture would occur. Also, if data are available, this index parameter can be varied to calibrate calculations to the measurements.

3.5.4 Sorption: Adsorption/Desorption And Cation Exchange

SESOIL includes two partitioning processes for movement of pollutant from soil moisture or soil air to soil solids. These are the sorption process and the cation exchange mechanism.

The sorption process may be defined as the adhesion of pollutant molecules or ions to the surface of soil solids. Most sorption processes are reversible, adsorption describing the movement of pollutant onto soil solids and desorption being the partitioning of the chemical from solid into the liquid or gas phase (Lyman et al., 1982). Adsorption and desorption are usually assumed to be occurring in equilibrium and are therefore modeled as a single process (Bonazountas et al., 1984). Adsorption is assumed to occur rapidly relative to the migration of the pollutant in soil moisture; it can drastically retard pollutant migration through the soil column.

SESOIL employs the general Freundlich equation (see Eq. 8 above) to model soil sorption processes. The equation correlates adsorbed concentration with the dissolved concentration of the pollutant, by means of an adsorption coefficient and the Freundlich parameter. This equation has been found to most nearly approximate the adsorption of many pollutants, especially organic chemicals, and a large amount of data have been generated and are available in the literature (see Bonazountas and Wagner, 1984; Fairbridge and Finke, 1979; Lyman et al., 1982).

For most organic chemicals, adsorption occurs mainly on the organic carbon particles within the soil (Lyman et al., 1982). The organic carbon partition coefficient (K_{oc}) for organic chemicals can be measured or estimated (Lyman et al., 1982). K_{oc} is converted to the partition coefficient (K_d) by multiplying by the fraction of organic carbon in the soil.

Values for the Freundlich exponent can be found in the literature. They generally range between 0.7 and 1.1, although values can be found as low as 0.3 and as high as 1.7. In the absence of data, a value of 1.0 is recommended since no estimation techniques for this parameter have yet been developed. Note that using 1.0 for the Freundlich exponent assumes a linear model for sorption (see Eq. 8).

The user is cautioned regarding indiscriminately using literature values for the partition coefficient K_d or the Freundlich exponent n, or estimation methods for K_d. There can be much variability in the values that are estimated or found in the literature compared to actual measurements for a site. For examples, refer to the study of Melancon et al. (1986).

Another option for modeling adsorption in SESOIL uses cation exchange capacity (CEC). Cation exchange occurs when positively charged atoms or molecules (cations such as heavy metals) are exchanged with the cations of minerals and other soil constituents. CEC is a measure amount of cations per unit of soil that are available for exchange with the pollutant.

The cation exchange algorithm in SESOIL is very simple and estimates the maximum amount of pollutant that can be adsorbed. The calculation of the pollutant immobilized by cation exchange is given by (from Bonazountas and Wagner, 1984):

$$MCEC = a \bullet CEC \bullet MWT / VAL \qquad (14)$$

where:

$MCEC$ = maximum pollutant cation exchanged by the soil (µg/g soil),

a = 10.0 (units coefficient),

CEC = cation exchange capacity of the soil (meq/100 g of dry wt. soil),

MWT = molecular weight of the pollutant cation (g/mol),

VAL = valence of the cation (-).

☐ ***Side Note:*** *The cation exchange algorithm has been verified to be computationally correct in SESOIL, but it has not been validated with measured data.*

With clays, the exchanged ion is often calcium, and clay soils tend to have the highest cation exchange capacity. Note that the CEC value of a soil increases with increase in pH, but pH is not included in the CEC algorithm in SESOIL. The CEC value must be adjusted manually to include effects due to pH.

In SESOIL, cation exchange computed by Eq. 14 is assumed to occur instantaneously, and irreversibly. Once maximum adsorption via exchange has been reached, no additional adsorption will be calculated. The process is also assumed to take precedence over all other soil processes in competition for the pollutant cation.

The use of the cation exchange subroutine is optional. If it is used, Eq. (8) should not be used (i.e., model inputs for K_d and K_{oc} should be 0.0) unless the user has selected the model inputs in such a way as to avoid double accounting. It is up to the user to be sure that cation exchange is the predominant adsorption mechanism at the modeled site. This determination includes considerations of leachate characteristics such as pH, ionic strength, and the presence and concentration of other cations. The other cations, often found in landfill leachate and aqueous industrial wastes, may have higher affinity for exchange with soil cations, and may effectively block exchange between the pollutant and the soil cations. In addition, the speciation of the pollutant should be considered (Bonazountas and Wagner, 1984).

3.5.5 Degradation: Biodegradation And Hydrolysis

The pollutant cycle of SESOIL contains two transformation routines which can be used to estimate pollutant degradation in the soil. Biodegradation is the biologic breakdown of organic chemicals, most often by microorganisms. Hydrolysis is a chemical reaction of the pollutant with water. Both processes result in the loss of the original pollutant and the creation of new chemicals. The SESOIL model accounts for the mass of original pollutant lost via degradation but does not keep track of any degradation products. The user is responsible for knowing what the degradation products will be and their potential significance.

The biodegradation process is usually a significant loss mechanism in soil systems since soil environments have a diverse microbial population and a large variety of food sources and habitats (Hamaker,1972). Many environmental factors affect the rate of biodegradation in soil, including pH, moisture content of the soil, temperature, redox potential, availability of nutrients, oxygen content of the soil air, concentration of the chemical, presence of appropriate microorganisms, and presence of other compounds that may be preferred substrates. However, SESOIL doesn't consider these factors.

Biodegradation in SESOIL is handled as primary degradation, which is defined as any structural transformation in the parent compound which results in a change in the chemical's identity. It is estimated using the chemical's rate of decay in both the dissolved and adsorbed phases according to the first-order rate equation:

$$P_d = (C \bullet \theta \bullet k_{dl} + S \bullet \rho_b \bullet k_{ds}) \bullet A \bullet d_s \bullet \Delta t \qquad (15)$$

where:

P_d = decayed pollutant mass during time step Δt (μg),

k_{dl} = biodegradation rate of the compound in the liquid phase (day^{-1}),

k_{ds} = biodegradation rate of the compound in the solid phase (day^{-1}),

A = area of pollutant application (cm^2),

d_s = depth of the soil sublayer (cm),

Δt = time step (day), and

c, θ, s, and ρ_b are as defined for Eqs. (8) and (9).

Note that c, θ, and s are functions of time in the SESOIL model.

The use of a first-order rate equation is typical for fate and transport models and generally is an adequate representation of biodegradation for many chemicals. However, due to the many factors affecting biodegradation, in some cases a first-order rate may not be applicable to the site field conditions and a zero-order or a second- or higher-order rate might be more appropriate. The biodegradation algorithm in SESOIL that is described by Eq. (15) can not handle these cases.

The user is cautioned regarding the use of literature values for the biodegradation rates since these values are quite variable and in many cases are not applicable to site field conditions. In most cases, biodegradation rates are very site-specific and uncertainty in these rates must be recognized. The user-supplied first-order decay rate constants (for moisture and solids) should be values measured for the pollutant in a soil culture test under conditions similar to the site being modeled.

The SESOIL hydrolysis algorithm allows the simulation of neutral, acid- or base-catalyzed reactions and assumes that both dissolved and adsorbed pollutant are susceptible to hydrolysis (Lyman et al., 1982). Since hydrolysis is the reaction of the pollutant with water, this reaction may occur at any depth as the pollutant moves through the soil column. The hydrolysis subroutine requires user-supplied rate constants for the neutral, acid and base hydrolysis reactions of the pollutant, and the pH for each soil layer. The model does not correct for the temperature of the modeled soil.

☐ **Side Note:**
The hydrolysis algorithm has been verified but has not been validated.

As for the biodegradation process, the algorithm for hydrolysis uses Eq. (15) except the rates k_d and k_{ds} are both replaced by the rate constant k_h, defined as (from Bonazountas and Wagner, 1984):

$$k_h = k_o + k_H [H^+] + k_{OH} [OH^-] \qquad (16)$$

where:

k_h = the hydrolysis rate constant (day^{-1}),

k_o = rate constant for neutral hydrolysis (day^{-1}),

k_H = rate constant for acid-catalyzed hydrolysis ($days^{-1} mol^{-1} L$),

$[H^+]$ = 10^{-pH}, the hydrogen ion concentration (mol/L),

k_{OH} = rate constant for base-catalyzed hydrolysis ($days^{-1} mol^{-1} L$), and

$[OH^-]$ = 10^{pH-14}, the hydroxyl ion concentration (mol/L).

If cation exchange is considered, the following formula is used:

$$P_d = MCEC \bullet k_h \bullet \rho_b \bullet A \bullet d_s \bullet \Delta t \qquad (17)$$

where the parameters are as defined for Eqs. (9), (14), (15), and (16).

Extrapolating hydrolysis rates measured in a laboratory to the environment increases the uncertainty of model results if the hydrolysis rate is not corrected for the influences of temperature, adsorption, the soil ionic strength, and the possible catalytic effect of dissolved material or solid surfaces. Since there are usually large uncertainties in hydrolysis rates, the SESOIL model results for hydrolysis should be considered only as approximations. The rate of hydrolysis for various organic chemicals may vary over more than 14 orders of magnitude. In addition, the hydrolysis routine does not consider the influence of ionic strength or the presence of other dissolved organics on the hydrolysis rate of the pollutant.

☐ ***Side Note:***
The complexation routine has been verified but has not been validated.

3.5.6 Metal Complexation

Complexation, also called chelation, is defined here as a transformation process. In SESOIL, complexation incorporates the pollutant as part of a larger molecule and results in the binding of the pollutant to the soil. For example, metal cations (e.g. copper, lead, iron, zinc, cadmium) combine with organic or other nonmetallic molecules (ligands) to form stable complexes. The complex that is formed will generally prevent the metal from undergoing other reactions or interactions of the free ion.

The pollutant fate cycle incorporates a simplified representation of the complexation process as a removal process. It is only available for scenarios in which the pollutant is a heavy metal. The model assumes a reversible process in which a metal ion is complexed by a specified soluble organic ligand to form a complex which is soluble, non-adsorbable, and non-migrating. Possible ligands are humic acid, fulvic acid, and low molecular weight carboxylic acids, which are commonly found in landfill leachate (Bonazountas and Wagner, 1984). It is the responsibility of the user to determine whether this process is likely to occur in the scenario being modeled, and to supply the appropriate information.

The complexation subroutine employs a nonlinear equation which must be solved numerically. It uses the same iterative procedure as the general pollutant cycle for monthly simulations. Required data include the stability (or dissociation) constant for the specific complex, and the mole ratio of ligand to metal. Also required are the molecular weights of the pollutant metal and the organic ligand. Equations used by this subroutine are based on the work of Giesy and Alberts (1984), Brinkman and Bellama (1978), and Sposito (1981). The model does not consider competition with metal ions in the soil which may have higher affinity for the ligand. Note that if the user chooses to model both cation exchange and metal complexation, the cation exchange process is assumed to occur first; ions involved in cation exchange are then unavailable for complexation. The general adsorption processes are modeled as being competitive with the complexation process (Bonazountas and Wagner, 1984).

3.5.7 Pollutant In Surface Runoff And Washload

Pollutant can be removed from the soil area being simulated by SESOIL via surface runoff and washload. The pollutant in surface runoff is simply the surface runoff computed in the hydrologic cycle (for each month) multiplied by the pollutant concentration in the soil moisture of the surface layer (for each time step). The result of this calculation is multiplied by another user-supplied parameter called ISRM, which controls the amount of chemical partitioned into runoff. There is no basis for estimating ISRM a priori; it can be set to 0.0 to "turn off" the pollutant participation in runoff, or it can be used essentially as a fitting parameter if data are available. In a calibration/validation exercise used to predict atrazine runoff at a site in Watkinsville, Georgia, the parameter ISRM was found to be 0.06 (see Hetrick et al., 1989).

Pollutant loss via washload is computed by taking the sediment yield from the washload cycle multiplied by the adsorbed pollutant concentration in the surface layer. While studies have been conducted comparing results of sediment yield with field data (Hetrick and Travis, 1988), pollutant loss via washload has not been validated in SESOIL.

3.5.8 Soil Temperature

The original SESOIL model assumed that soil temperature was equal to the user-supplied air temperature. The model was modified by Hetrick et al. (1989) to predict soil temperature from air temperature according to the following (Toy et al., 1978):

Summer: $Y = 16.115 + 0.856X,$
Fall: $Y = 1.578 + 1.023X,$
Winter: $Y = 15.322 + 0.656X,$
Spring: $Y = 0.179 + 1.052X,$
where:
Y = the mean monthly soil temperature (°F).
X = the mean monthly air temperature (°F).

These regression equations are very crude and not depth dependent. However, further complexity is not warranted since soil temperature is used only in Eq. (7) and does not significantly affect results. It should be noted that some chemical parameters and processes are dependent on temperature (for example, solubility, Henry's law constant, and rate constants for biodegradation and hydrolysis). No explicit consideration of these effects is included in SESOIL, and the user should adjust the input values for such parameters if temperature effects are judged to be important.

3.5.9 Pollutant Cycle Evaluation

There are several approaches used to evaluate the reliability and usefulness of an environmental model, such as verification, calibration, sensitivity analysis, uncertainty analysis, and validation. Verification establishes that results from each of the algorithms of the model are correct. Calibration is the process of adjusting selected model parameters within an accepted range until the differences between model predictions and field observations are within selected criteria of performance (Donnigan and Dean, 1985). Sensitivity analysis focuses on the relative impact each parameter or term has on the model output, in order to determine the effect of data quality on output reliability. Uncertainty analysis seeks to quantify the uncertainty in the model output as a function of uncertainty in both model input and model operations. Validation also compares measured with predicted results, but includes analysis of the theoretical foundations of the model, focusing on the model's performance in simulating actual behavior of the chemical in the environment under study. (Note that the term validation has often been broadly used to mean a variety of things, including all five of the techniques mentioned above.)

A number of calibration, validation, and sensitivity studies have been performed on the SESOIL model. The model has been verified by extensive testing using extreme ranges of input data. Studies of the hydrologic and washload cycles have already been discussed above (see Sections 3.3 and 3.4). The following discusses the kinds of evaluations that have been performed on the pollutant cycle of the SESOIL model. Note that model validation is a continuing process; no model is ever completely validated.

To assess SESOIL's predictive capabilities for pollutant movement, a pollutant transport and validation study was performed by Arthur D. Little, Inc. under contract to EPA (Bonazountas et al., 1982). The application/validation study was conducted on two field sites, one in Kansas and one in Montana. SESOIL results were compared to data for the metals chromium, copper, nickel, and sodium at the Kansas site and the organics naphthalene and anthracene at the Montana site. Results showed reasonable agreement between predictions and measurements, although the concentrations of the metals were consistently underestimated, and the rate of metal movement at the Kansas site was consistently overestimated. At the Montana site, the concentrations of the organics were overestimated by SESOIL. Bonazountas et al. (1982) state that the overestimations for the organics were probably due to the fact that biodegradation was not considered in the simulations. Note that this study was done with the original SESOIL model, not the modified model that is described herein.

Hetrick et al. (1989) compared predictions of the improved version of SESOIL with empirical data from a laboratory study involving six organic chemicals (Melancon et al., 1986) and from three different field studies involving the application of aldicarb to two field plots (Hornsby et al., 1983; R. L. Jones, 1986; Jones et al., 1983, 1985) and atrazine to a single-field watershed (Smith et al., 1978). Results for several measures of pollutant transport were compared including the location of chemical peak vs. time, the time-dependent amount of pollutant leached to groundwater, the depth distribution of the pollutant at various times, the mass of the chemical degraded, and the amount of pollutant in surface runoff. This study showed that SESOIL predictions were in good agreement with observed data for both the laboratory study and the field studies.

SESOIL does a good job of predicting the leading edge of the chemical profile (Hetrick et al., 1989), due mainly to the improvement of the pollutant depth algorithm to include the chemical sorption characteristics (see Section 3.5.2 above). Also, when a split-sample calibration/validation procedure was used on 3 years of data from the single-field watershed, SESOIL did a good job of predicting the amount of chemical in the runoff. The model was less effective in predicting actual concentration profiles; the simulated concentrations near the soil surface underestimated the measurements in most cases. One explanation is that SESOIL does not consider the potential upward movement of the chemical with the upward movement of water due to soil evaporation losses.

SESOIL is a useful screening-level chemical migration and fate model. The model is relatively easy to use, the input data are straightforward to compile, and most of the model parameters can be readily estimated or obtained. Sensitivity analysis studies with SESOIL can be done efficiently. SESOIL can be applied to generic environmental scenarios for purposes of evaluating the general behavior of chemicals. Care should be taken when applying SESOIL to sites with large vertical variations in soil properties since the hydrologic cycle assumes a homogeneous soil profile. Only one value for the soil moisture content is computed for the entire soil column. If different permeabilities are input for each soil layer, the soil moisture content calculated in the hydrologic cycle using the vertically-averaged permeability (Eq. 3) may not be valid for the entire soil column. Thus, the user is warned that even though the model can accept different permeabilities for each layer, the effects of variable permeability are not fully accounted for by the model.

It is recommended that predictions for the hydrology at a given site be calibrated to agree with known measurements. Caution should be used when making conclusions based on modeling results when little hydrologic data exist against which to calibrate predictions. In these cases, it is recommended that the user employ sensitivity analysis or evaluate results obtained by assigning distributions to the input parameters (e.g., see Gardner, 1984; O'Neill et al., 1982; Hetrick et al., 1991). However, when properly used, SESOIL is an effective screening-level tool in assessing chemical movement in soils.

SESOIL MODEL INPUT DATA

```
(1) APPLICATION INPUT DATA
  1 ELLSWORTH APPLIC DATA
 -ILYS,IYRS,AR,L,ISPILL,ISUMRS,ICONC   2.00  1.00 10000.  43.00  1  1  1
 -D1,D2,D3,D4,NSUBL1 to NSUBL4        30.48  60.96  0.00  0.00  1  1  0  0
 -PH1,PH2,PH3,PH4              7.00  7.00  7.00  7.00
 -K11,K12,K13,K14              1E-7  1E-7  1E-7  1E-7
 -KDEL MULTIPLIERS               1.00  1.00  1.00
 -KDES MULTIPLIERS               1.00  1.00  1.00
 -OC MULTIPLIERS                1.00  1.00  1.00
 -CEC MULTIPLIERS                1.00  1.00  1.00
 -FRN MULTIPLIERS                1.00  1.00  1.00
 -ADS MULTIPLIERS                1.00  1.00  1.00
            **** LAYER 1 **  YEAR 1 ****
 POLIN16440.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 TRANS1  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 SINK1   0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 LIG1    0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 VOLF1   0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 ISRM    0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 ASL     0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
            **** LAYER 2 **  YEAR 1 ****
 POLIN212880.0 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 TRANS2  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 SINK2   0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 LIG2    0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 VOLF2   0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
            **** LAYER 3 **  YEAR 1 ****
 POLIN3  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 TRANS3  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 SINK3   0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 LIG3    0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 VOLF3   1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
            **** LAYER 4 **  YEAR 1 ****
 POLIN4  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 TRANS4  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 SINK4   0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 LIG4    0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 VOLF4   1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00

 SUMMERS MODEL PARAMETERS FOLLOW
(SATCON,HYDGRA,THICKS,WIDTH,BACKCA)
     117.34 0.017 304.  100.  0.0000
```

```
INITIAL CONTAMINANT CONCENTRATIONS FOLLOW
MONTH IN YEAR 1 FOR LOADING CONC.'S    1.0
CONCIN1  00.0  0.00  0.00
CONCIN2  00.0  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
CONCIN3  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
CONCIN4  0.00  0.00  0.00
 999 END OF FILE

(2)  CLIMATOLOGICAL INPUT DATA
   1 ELLSWORTH AIR FORCE BASE, AREA D                  1
      ****  YEAR 1  ****
TA    27.50 19.80 14.85 12.65 14.86 18.15 25.30 30.87 35.75 40.73 39.68 34.10
NN       0.48  0.54  0.51  0.52  0.55  0.60  0.56  0.57  0.48  0.43  0.39  0.43
S       0.63  0.62  0.61  0.61  0.62  0.66  0.59  0.65  0.64  0.59  0.62  0.63
A        0.25  0.20  0.20  0.20  0.20  0.25  0.30  0.40  0.40  0.45  0.50  0.40
REP      0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
MPM       2.41  1.65  1.06  1.17  1.55  2.41  4.67  7.67  4.98  3.83  2.77  2.10
MTR       0.46  0.49  0.60  0.61  0.50  0.50  0.40  0.40  0.30  0.30  0.20  0.30
MN        5.00  5.00  6.00  6.00  6.00  8.00  8.00 11.00 11.00  8.00  7.00  6.00
MT    30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40
   2 OAK RIDGE ATDL                                 1
      ****  YEAR 1  ****
TA       14.88  8.38  4.00  3.44  4.72  8.66 14.44 18.94 22.94 24.50 24.00 20.83
NN        0.50  0.60  0.65  0.70  0.65  0.65  0.60  0.60  0.60  0.60  0.55  0.50
S       0.70  0.70  0.70  0.70  0.70  0.65  0.65  0.70  0.70  0.70  0.75  0.75
A        0.16  0.16  0.17  0.19  0.19  0.17  0.16  0.16  0.16  0.16  0.16  0.16
REP      0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
MPM   7.71 11.52 14.42 12.62 11.81 15.03 11.43 10.99 10.73 13.12  9.48  9.73
MTR       0.46  0.49  0.60  0.61  0.57  0.52  0.46  0.41  0.33  0.30  0.28  0.44
MN        4.51  5.80  6.38  6.67  6.54  7.35  6.58  6.93  6.58  7.67  6.22  5.00
MT    30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40 30.40
 999 END OF FILE

(3)  SOIL INPUT DATA
   1 SAND
      -  RS,K1,C,N,OC                 2.34   0.00   3.70   0.30   0.42
      -  CEC,FRN                    0.00   1.00
 999 END OF FILE

(4)  CHEMICAL INPUT DATA
   1 TOTAL BTEX
      - SL,DA,H,KOC,K               1750.00  0.017   0.005 50.00   0.00
      - MWT,VAL,KNH,KBH,KAH            106.17   0.00   0.00   0.00   0.00
      - KDEL,KDES,SK,B,MWTLIG          0.00   0.00   0.00   0.00   0.00
 999 END OF FILE
```

```
           SESOIL-84 : SEASONAL CYCLES OF WATER, SEDIMENT,
               AND POLLUTANTS IN SOIL ENVIRONMENTS

DEVELOPERS: M. BONAZOUNTAS,ARTHUR D. LITTLE INC.  ,(617)864-5770,X5871
J. WAGNER     ,DIS/ADLPIPE, INC.,(617)492-1991,X5820

MODIFIED EXTENSIVELY BY
D.M. HETRICK
OAK RIDGE NATIONAL (615) 576-7556
VERSION   : OCTOBER,

****** MONTHLY SESOIL MODEL OPERATION ******
                 MONTHLY SITE SPECIFIC SIMULATION
 RUN:  1

 REGION          : (    1)      ELLSWORTH AIR FORCE BASE, AREA D
 SOIL TYPE        : (    1)      SAND
 COMPOUND         : (    1)      TOTAL BTEX
 WASHLOAD DATA   : (    0)
 APPLICATION AREA: (    1)      ELLSWORTH APPLIC DATA

    GENERAL INPUT PARAMETERS
    ========================
    -- SOIL INPUT PARAMETERS --

 SOIL DENSITY (G/CM**3):                          2.34
 INTRINSIC PERMEABILITY (CM**2):                        .000E+00
 DISCONNECTEDNESS INDEX (-):                           3.70
 POROSITY (-):                              .300
 ORGANIC CARBON CONTENT (%):                            .420
 CATION EXCHANGE CAPACITY (MILLI EQ./100G DRY SOIL):     .000E+00
 FREUNDLICH EXPONENT (-):                          1.00
1

    -- CHEMICAL INPUT PARAMETERS --

 SOLUBILITY (UG/ML):                             .175E+04
 DIFFUSION COEFFICIENT IN AIR (CM**2/SEC):              .170E-01
 HENRYS LAW CONSTANT (M**3-ATM/MOLE):                    .000E+00
 ADSORPTION COEFFICIENT ON ORGANIC CARBON(KOC):           550.
 ADSORPTION COEFFICIENT ON SOIL (K):                  .000E+00
 MOLECULAR  WEIGHT (G/MOL):                       106.
 VALENCE (-):                                .000E+00
 NEUTRAL HYDROLYSIS CONSTANT (/DAY):                   .000E+00
 BASE HYDROLYSIS CONSTANT (L/MOL-DAY):                  .000E+00
 ACID HYDROLYSIS CONSTANT (L/MOL-DAY):                  .000E+00
 DEGRADATION RATE IN MOISTURE (/DAY):                  .000E+00
 DEGRADATION RATE ON SOIL (/DAY):                   .000E+00
 LIGAND-POLLUTANT STABILITY CONSTANT (-):                 .000E+00
 NO. MOLES LIGAND/MOLE POLLUTANT (-):                   .000E+00
 LIGAND MOLECULAR WEIGHT (G/MOL):                    .000E+00
```

```
      -- APPLICATION INPUT PARAMETERS --

    NUMBER OF SOIL LAYERS:                          2
    YEARS TO BE SIMULATED:                         20
    AREA (CM**2):                         0.100E+05
    APPLICATION AREA LATITUDE (DEG.):                    43.0
    SPILL (1) OR STEADY APPLICATION (0):                1
    MODIFIED SUMMERS MODEL USED (1) OR NOT (0) FOR GWR. CONC.: 1
    INITIAL CHEMICAL CONCENTRATIONS GIVEN (1) OR NOT GIVEN (0) 1
    DEPTHS (CM):                          30.    61.
    NUMBER OF SUBLAYERS/LAYER                              1      1
    PH (CM):                           7.0     7.0
    INTRINSIC PERMEABILITIES (CM**2):                 0.10E-08 0.10E-08
    KDEL RATIOS (-):                        1.0
    KDES RATIOS (-):                        1.0
    OC RATIOS (-):                         1.0
    CEC RATIOS (-):                         1.0
    FRN RATIOS(-):                          1.0
    ADS RATIOS(-):                          1.0
   1
      YEAR -  1   MONTHLY INPUT PARAMETERS
      ========   ======================

      -- CLIMATIC INPUT PARAMETERS --

                           OCT     NOV     DEC     JAN     FEB     MAR     APR     MAY     JUN
JUL     AUG     SEP
    TEMP. (DEG C)      27.500  19.800  14.850  12.650  14.860  18.150  25.300  30.870  35.750
40.730  39.680  34.100
     CLOUD CVR (FRAC.)    0.480   0.540   0.510   0.520   0.550   0.600   0.560   0.570   0.480
0.430   0.390   0.430
     REL. HUM.(FRAC.)    0.630   0.620   0.610   0.610   0.620   0.660   0.590   0.650   0.640
0.590   0.620   0.630
     ALBEDO (-)        0.250   0.200   0.200   0.200   0.200   0.250   0.300   0.400   0.400   0.450
0.500   0.400
     EVAPOT. (CM/DAY)     0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.000   0.000
     PRECIP. (CM)        2.410   1.650   1.060   1.170   1.550   2.410   4.670   7.670   4.980   3.830
2.770   2.100
     M.TIME RAIN(DAYS)    0.460   0.490   0.600   0.610   0.500   0.500   0.400   0.400   0.300
0.300   0.200   0.300
     M. STORM NO. (-)     5.000    5.000   6.000   6.000   6.000   8.000   8.000  11.000  11.000
8.000   7.000   6.000
     M. SEASON (DAYS)    30.400  30.400  30.400  30.400  30.400  30.400  30.400  30.400
30.400  30.400  30.400  30.400

    INITIAL POLLUTANT CONCENTRATIONS IN UG/ML, INPUT FOR MONTH  0 OF YEAR 1
     LAYER 1:
       SUBLAYER         1
     INITIAL CONC. (UG/ML)  0.00E-01
     LAYER 2:
       SUBLAYER         1
     INITIAL CONC. (UG/ML)  1.00E+00
```

```
        -- POLLUTANT INPUT PARAMETERS --

                        OCT    NOV    DEC    JAN    FEB    MAR    APR    MAY    JUN    JUL
AUG    SEP

     POL. INP-1 (UG/CM**2)  4.40E+02 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     TRNSFORMD-1 (UG/CM**2) 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     SINKS-1 (UG/CM**2)     0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     LIG.INPUT-1 (UG/CM**2) 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     VOLATILIZATION MULT.-1 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     SURFACE RUNOFF MULT.   0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     POL. IN RAIN (FRAC-SL) 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     POL. INP-L (UG/CM**2)  2.88E+03 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     TRNSFORMD-L (UG/CM**2) 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     SINKS-L (UG/CM**2)     0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     LIG.INPUT-L (UG/CM**2) 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     VOLATILIZATION MULT.-L 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
0.00E-01 0.00E-01 0.00E-01 0.00E-01 0.00E-01
     1
        YEARS -  2-20   MONTHLY INPUT PARAMETERS
        ========   =====================

        -- CLIMATIC INPUT PARAMETERS ARE SAME AS LAST YEAR

        -- POLLUTANT INPUT PARAMETERS ARE SAME AS LAST YEAR

        YEAR -  1   MONTHLY RESULTS (OUTPUT)
        ========   =====================

        -- HYDROLOGIC CYCLE COMPONENTS --

                        OCT    NOV    DEC    JAN    FEB    MAR    APR    MAY    JUN    JUL
AUG    SEP
     MOIS. IN L1 (%)      8.124   7.704   7.134   7.314   7.734   8.514   9.714  10.794   9.444
8.544   7.854   7.494
     MOIS. BELOW L1 (%)   8.124   7.704   7.134   7.314   7.734   8.514   9.714  10.794   9.444
8.544   7.854   7.494
     PRECIPATION (CM)     2.421   1.648   1.067   1.163   1.550   2.413   4.635   7.602   5.027
3.853   2.770   2.105
     NET INFILT. (CM)     2.421   1.648   1.067   1.163   1.550   2.413   4.635   7.602   5.026
3.853   2.770   2.105
     EVAPOTRANS. (CM)     5.594   2.360   1.006   1.435   3.486   5.791   9.491  10.276  13.198
13.162   9.929   7.960
```

```
     MOIS. RETEN (CM)    -0.041  -0.032  -0.043   0.014   0.032   0.059   0.091   0.082  -0.103  -
0.069  -0.053  -0.027
     SUR. RUNOFF (CM)     0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000
0.000   0.000   0.000
     GRW. RUNOFF (CM)    -3.132  -0.680   0.105  -0.286  -1.968  -3.438  -4.948  -2.757  -8.069
-9.241  -7.107  -5.828
     YIELD (CM)         -3.132  -0.680   0.105  -0.286  -1.968  -3.438  -4.947  -2.756  -8.069  -
9.241  -7.107  -5.828
     PAU/MPA (GZU)        1.005   0.999   1.007   0.994   1.000   1.001   0.992   0.991   1.009
1.006   1.000   1.002
     PA/MPA (GZ)        1.005   0.999   1.007   0.994   1.000   1.001   0.992   0.991   1.009   1.006
1.000   1.002

    -- POLLUTANT MASS DISTRIBUTION IN COLUMN (UG) -- NOTE: IF COMPONENT IS ZERO
EACH MONTH, IT IS NOT PRINTED
       --------------------------------------------------------------------------------------------
        UPPER SOIL ZONE:
           SUBLAYER  1
     IN SOIL MOI 6.376E+04 5.995E+04 5.532E+04 5.638E+04 5.876E+04 6.314E+04 6.926E+04
7.376E+04 6.151E+04 5.300E+04 4.696E+04 4.349E+04
     ADS ON SOIL 4.242E+06 4.207E+06 4.192E+06 4.167E+06 4.107E+06 4.009E+06 3.854E+06
3.694E+06 3.521E+06 3.353E+06 3.232E+06 3.137E+06

        LOWER SOIL ZONE:
           SUBLAYER  1
     IN SOIL MOI 4.278E+05 4.065E+05 3.771E+05 3.868E+05 4.095E+05 4.516E+05 5.167E+05
5.761E+05 5.085E+05 4.635E+05 4.284E+05 4.104E+05
     ADS ON SOIL 2.847E+07 2.853E+07 2.857E+07 2.859E+07 2.862E+07 2.867E+07 2.875E+07
2.885E+07 2.910E+07 2.932E+07 2.948E+07 2.960E+07

        -- POLLUTANT CONCENTRATIONS (UG/ML) OR (UG/G) -- NOTE: IF
CONCENTRATIONS ARE ZERO FOR EACH MONTH, THEY ARE NOT PRINTED --
        ----------------------------------------------------------------------------------------------------
----
        UPPER SOIL ZONE:
           SUBLAYER  1
     MOISTURE    2.575E+00 2.553E+00 2.544E+00 2.529E+00 2.493E+00 2.433E+00 2.339E+00
2.242E+00 2.137E+00 2.035E+00 1.962E+00 1.904E+00
     %SOLUBILITY 1.471E-01 1.459E-01 1.454E-01 1.445E-01 1.424E-01 1.390E-01 1.337E-01
1.281E-01 1.221E-01 1.163E-01 1.121E-01 1.088E-01
     ADSORBED    5.948E+00 5.898E+00 5.877E+00 5.842E+00 5.758E+00 5.621E+00 5.404E+00
5.179E+00 4.936E+00 4.701E+00 4.532E+00 4.398E+00

        LOWER SOIL ZONE:
           SUBLAYER  1
     MOISTURE    8.639E+00 8.657E+00 8.671E+00 8.676E+00 8.686E+00 8.701E+00 8.726E+00
8.756E+00 8.832E+00 8.899E+00 8.948E+00 8.983E+00
     %SOLUBILITY 4.936E-01 4.947E-01 4.955E-01 4.958E-01 4.963E-01 4.972E-01 4.986E-01
5.003E-01 5.047E-01 5.085E-01 5.113E-01 5.133E-01
     ADSORBED    1.996E+01 2.000E+01 2.003E+01 2.004E+01 2.006E+01 2.010E+01 2.016E+01
2.023E+01 2.040E+01 2.056E+01 2.067E+01 2.075E+01
     POL DEP CM  6.101E+01 6.109E+01 6.117E+01 6.123E+01 6.127E+01 6.131E+01 6.144E+01
6.181E+01 6.187E+01 6.187E+01 6.187E+01 6.187E+01
```

```
1                    YEAR -   1 ANNUAL SUMMARY REPORT
                     ===================================
      -- TOTAL INPUTS (UG) --
  UPPER SOIL ZONE          4.400E+06
  LOWER SOIL ZONE           2.880E+07

        -- HYDROLOGIC CYCLE COMPONENTS --

  AVERAGE SOIL MOISTURE ZONE 1 (%)            8.364
  AVERAGE SOIL MOISTURE BELOW ZONE 1 (%)        8.364
  TOTAL PRECIPITATION (CM)               36.254
  TOTAL INFILTRATION (CM)               36.253
  TOTAL EVAPOTRANSPIRATION (CM)             83.689
  TOTAL SURFACE RUNOFF (CM)              0.000
  TOTAL GRW RUNOFF (CM)               -47.346
  TOTAL MOISTURE RETENTION (CM)           -0.089
  TOTAL YIELD (CM)               -47.345

  -- AVERAGE POLLUTANT CONCENTRATIONS --  NOTE: ONLY NON-ZERO VALUES ARE
PRINTED --
                    ------------------------------------------------------------------------------------


    UPPER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  2.312E+00
                    ADSORBED SOIL (UG/G)   5.341E+00

    LOWER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  8.764E+00
                    ADSORBED SOIL (UG/G)   2.025E+01
                    MAX. POLL. DEPTH (M)   6.187E-01

1                    YEAR -   5 ANNUAL SUMMARY REPORT
                     ===================================
  -- AVERAGE POLLUTANT CONCENTRATIONS
    UPPER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  6.696E+00
                    ADSORBED SOIL (UG/G)   1.547E+01

    LOWER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  4.620E+01
                    ADSORBED SOIL (UG/G)   1.067E+02
                    MAX. POLL. DEPTH (M)   6.552E-01

                     YEAR -  10 ANNUAL SUMMARY REPORT
                     ===================================
  AVERAGE POLLUTANT CONCENTRATIONS
    UPPER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  8.020E+00
                    ADSORBED SOIL (UG/G)   1.853E+01

   LOWER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  9.505E+01
                    ADSORBED SOIL (UG/G)   2.196E+02
                    MAX. POLL. DEPTH (M)   7.007E-01

               YEAR -  15 ANNUAL SUMMARY REPORT
               ================================

-- AVERAGE POLLUTANT CONCENTRATIONS
   UPPER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  8.281E+00
                    ADSORBED SOIL (UG/G)   1.913E+01

   LOWER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  1.437E+02
                    ADSORBED SOIL (UG/G)   3.319E+02
                    MAX. POLL. DEPTH (M)   7.463E-01

               YEAR -  20 ANNUAL SUMMARY REPORT
               ================================

AVERAGE POLLUTANT CONCENTRATIONS
-- UPPER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  8.333E+00
                    ADSORBED SOIL (UG/G)   1.925E+01

   LOWER SOIL ZONE:
      SUBLAYER  1
                    SOIL MOISTURE (UG/ML)  1.922E+02
                    ADSORBED SOIL (UG/G)   4.440E+02
                    MAX. POLL. DEPTH (M)   7.918E-01

********************EXECUTION COMPLETED******************************
```

SATURATED SOIL LEACHING CALCULATIONS

Saturated Soil Leaching Calculations
Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, SD

Knowns: (a) linear gw velocity = 0.4 ft/day
= 0.12 m/day

(b) porosity ≈ 0.35

(c) soil bulk density ≈ 2.34 g/cm^3

(d) max. saturated soil conc

Appendix A ⇒ MW-34 + MW-37

(e) groundwater BTEX conc available for MW-34

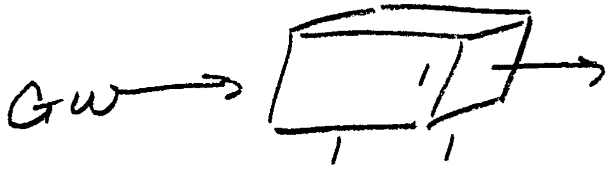
(f) Based on f_{oc} = 0.0042 and literature values of K_{oc} from Montgomery & Welkom 1990

K_d benzene = 0.000882
K_d toluene = 0.002016
K_d ethylbenzene = 0.00168
K_d xylenes = 0.002268

Assumptions:

(a) local equilibrium applies; equilibrium will be attained @ each new flush

(b) simulated mass = 1m^3



∴ mass of soil = 2,340 $\frac{kg}{m^3}$
mass of pore water = 350 $\frac{L}{m^3}$

(c) new volume of H$_2$O will pass through soil mass every

(velocity $0.12 \frac{m}{day}$ ⇒ 8.3 days/m)

∴ 3.6 flushes/mo

(d) assume % efficiency of leaching defined by conc. @ MW-34 in contact w/ soil. Will result in conservative estimate → "slow burners"

Equations:

$$(a) \quad K_d = \frac{\mu g/kg}{\mu g/L} = \frac{\text{mass adsorbed}}{\text{mass dissolved}}$$

$$\therefore \quad \frac{\mu g}{L} = \left(\mu g/kg * \underset{\sim 0.1\%}{\text{eff. factor}}\right) / K_d$$

$$(b) \quad M_T = M_{soil} + M_{water}$$

$$M_{soil\ remaining} = M_{soil} - M_{water}$$

$$\frac{\mu g}{kg} = \left(\frac{\mu g}{kg} - \frac{\mu g}{L}\right) \rightarrow$$ need to correct for density/vol.

$$\text{remember: } \frac{350\ L/m^3}{2340\ \frac{kg}{m^3}} \Rightarrow 0.149\ L/kg$$

$$\frac{\mu g}{kg_{remaining}} = \left(\frac{\mu g}{kg_{initial}} - \left(\frac{\mu g}{L_{(leached)}}\right)\right)\left(0.149 \frac{L}{kg}\right.$$

The following spreadsheet shows these calculations for the BTEX compounds. See text for discussion of results (Section 6)

SATURATED SOIL LEACHING CALCULATIONS
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Days	Benzene Soil Concen.	Water Concen.	Toluene Soil Concen.	Water Concen.	Ethylbenzene Soil Concen.	Water Concen.	Total Xylenes Soil Concen.	Water Concen.
0	13	219.6	66	487.8	260.0	216.7	880.0	570.4
8.3	1.0	16.9	33.0	243.9	227.7	189.8	795.0	515.3
16.6	0.5	8.4	15.0	110.9	199.4	166.2	718.2	465.5
24.9	0.1	0.8	7.0	51.7	174.7	145.6	648.9	420.6
33.2	0.0	0.0	3.5	25.9	153.0	127.5	586.2	380.0
41.5	0.0	0.0	0.0	0.0	134.0	111.7	529.6	343.3
49.8	0.0	0.0	0.0	0.0	117.4	97.8	478.5	310.1
58.1	0.0	0.0	0.0	0.0	102.8	85.7	432.2	280.2
66.4	0.0	0.0	0.0	0.0	90.0	75.0	390.5	253.1
74.7	0.0	0.0	0.0	0.0	78.8	65.7	352.8	228.7
83	0.0	0.0	0.0	0.0	69.1	57.5	318.7	206.6
91.3	0.0	0.0	0.0	0.0	60.5	50.4	287.9	186.6
99.6	0.0	0.0	0.0	0.0	53.0	44.1	260.1	168.6
107.9	0.0	0.0	0.0	0.0	46.4	38.7	235.0	152.3
116.2	0.0	0.0	0.0	0.0	40.6	33.9	212.3	137.6
124.5	0.0	0.0	0.0	0.0	35.6	29.7	191.8	124.3
132.8	0.0	0.0	0.0	0.0	31.2	26.0	173.3	112.3
141.1	0.0	0.0	0.0	0.0	27.3	22.7	156.6	101.5
149.4	0.0	0.0	0.0	0.0	23.9	19.9	141.4	91.7
157.7	0.0	0.0	0.0	0.0	20.9	17.5	127.8	82.8
166	0.0	0.0	0.0	0.0	18.3	15.3	115.4	74.8
174.3	0.0	0.0	0.0	0.0	16.1	13.4	104.3	67.6
182.6	0.0	0.0	0.0	0.0	14.1	11.7	94.2	61.1
190.9	0.0	0.0	0.0	0.0	12.3	10.3	85.1	55.2
199.2	0.0	0.0	0.0	0.0	10.8	9.0	76.9	49.8
207.5	0.0	0.0	0.0	0.0	9.5	7.9	69.5	45.0
215.8	0.0	0.0	0.0	0.0	8.3	6.9	62.8	40.7

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OILENS MODEL BACKGROUND, INPUT VALUES, AND RESULTS

EPA/600/R-94/039a
April 1994

THE HYDROCARBON SPILL SCREENING MODEL (HSSM)
VOLUME 1: USER'S GUIDE

by

James W. Weaver
Robert S. Kerr Environmental Research Laboratory
United States Environmental Protection Agency
Ada, Oklahoma 74820

Randall J. Charbeneau, John D. Tauxe
Department of Civil Engineering
The University of Texas at Austin
Austin, Texas 78712

Bob K. Lien
Robert S. Kerr Environmental Research Laboratory
United States Environmental Protection Agency
Ada, Oklahoma 74820

and

Jacques B. Provost
Computer Sciences Corporation
Ada, Oklahoma 74820

Robert S. Kerr Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Ada, Oklahoma 74820

2.2 OILENS

If a large enough volume of hydrocarbon is released, then the LNAPL reaches the water table. Typically this occurs in a relatively short time for LNAPLs, like gasoline, that have low viscosities. The OILENS module simulates radial spreading of the LNAPL phase at the water table and dissolution of the chemical constituent. If sufficient head is available, the water table is displaced downward; lateral spreading begins; and the OILENS portion of the model is triggered. OILENS is based on three major approximations. First, the LNAPL spreading is purely radial, which implies that the slope of the regional ground water table is small enough to be unimportant for the lens motion. Second, the thickness is determined by buoyancy alone (Ghyben-Herzberg relations). Third, the shape of the lens is given by the Dupuit assumptions, where flow is assumed horizontal and the gradient is approximated by the change in head over a horizontal distance. These three assumptions lead to an efficient formulation of the model, which is reflected in its low computational requirements.

The lens thickness in the formation and the lens radius both increase during the initial phase of spreading (Figure 2). The height of the lens depends on the LNAPL phase density and viscosity, the release characteristics, and the saturated hydraulic conductivity of the system. For example, in a given porous medium, diesel fuel would tend to form taller lenses than gasoline because of its higher viscosity. Initially the lenses build up height because the LNAPL enters the lens at a higher rate than it moves radially. Later, after the source rate declines, the lens thins while continuing to spread laterally. Residual hydrocarbon is left both above and below the actively spreading lens during this period (Figure 7). The thickness calculated by OILENS is an averaged thickness of the LNAPL in the formation (Appendix 3.3, Schwille, 1967) and is not necessarily directly related to the thicknesses observed in observation wells (Kemblowski and Chiang, 1990).

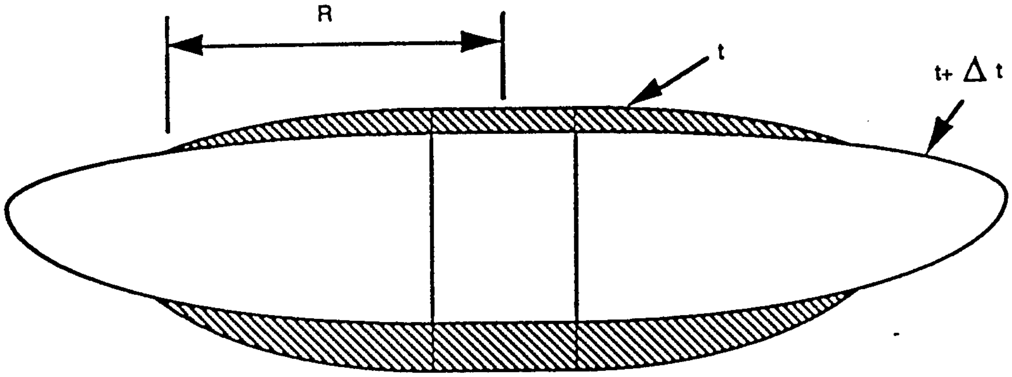

Figure 7 Lens configuration during thinning phase

Draft for Peer Review December 15, 1993

The Hydrocarbon Spill Screening Model (HSSM)
Volume 2: Theoretical Background

by

Randall J. Charbeneau
Center for Research in Water Resources
The University of Texas at Austin
Austin, Texas 78712

James W. Weaver
Robert S. Kerr Environmental Research Laboratory
United States Environmental Protection Agency
Ada, Oklahoma 74820

Robert S. Kerr Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Ada, Oklahoma 74820

$$\psi_{ow} = \frac{\rho_w \sigma_{ow}}{\Delta \rho_{ow} \sigma_{aw}} \psi_{aw} \tag{37}$$

$$\psi_{ao} = \frac{\rho_w \sigma_{ao}}{\rho_o \sigma_{aw}} \psi_{aw} \tag{38}$$

where ψ_{ij} is the capillary pressure head or capillary rise for the ij-fluid pair, ρ is the fluid density, σ is the interfacial tension, and $\Delta\rho_{ow}$ is the density difference between the hydrocarbon and water. For the oil-water system, its capillary rise is measured from z_{ao}. These allow the LNAPL thickness D_o to be calculated from its thickness as seen in an observation well, as shown in ~~?~~. 134 Figure 14 shows representative values of the effective LNAPL saturation as a function of average lens thickness for 35 API petroleum and for a gasoline in a sand soil.

7) The constituent mass is transported from the lens to groundwater by infiltrating water moving through the lens and by groundwater flowing beneath the lens and coming into contact with it. Equilibrium partitioning occurs between the hydrocarbon and water when they are in direct contact.

3.1 OILENS Model Development

The assumptions of vertical equilibrium, radial flow, and a steady-state hydrocarbon distribution lead to a simplified representation of the lens. At any given time the free product distribution is specified by three variables: the effective lens oil volumetric content, θ_o, the lens head beneath the source, h_{os}, and the radius of the lens, R_t. The lens oil content is specified as a constant input parameter and must be estimated from the conditions of the release. The remaining two variables, h_{os} and R_t, vary with time and must be calculated as part of the model. Their calculation is based on continuity principles, as described below.

From the Dupuit equation, the oil layer head at any radius $r > R_s$ is given by

Eq appears on page 39

In this last equation R_s is the source radius and R_t is the radius of the oil lens. Application of the continuity

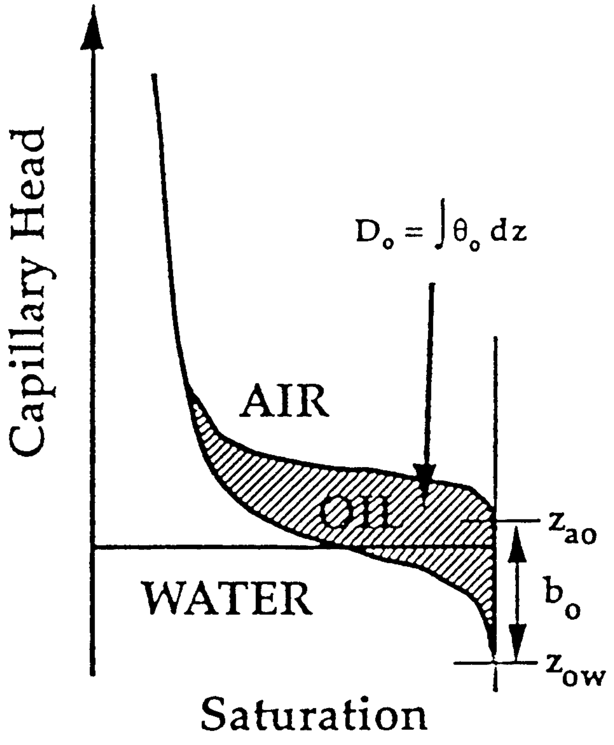

Figure 13A Calculation of LNAPL thickness in an oil lens

$$h_o(r) = h_{os} \sqrt{\frac{\ln\left(\frac{R_t}{r}\right)^2}{\ln\left(\frac{R_t}{R_s}\right)^2}} \qquad (39)$$

SEE PAGE 39A

Figure 14 Effective saturation of a hydrocarbon in a sand

principle to the vertical circular cylinder of the lens beneath the source zone, as shown in Figure 15, gives

$$Q_{KOPT} - Q_{radial} - Q_{loss} = \pi R_s^2 \theta_o \beta \frac{dh_{os}}{dt} \qquad (40)$$

In equation (40), Q_{KOPT} is the inflow to the lens from the vadose zone as calculated by the KOPT model, Q_{radial} is the lateral flow from the circular cylinder, Q_{loss} includes the volume of oil dissolved from the central cylinder plus the oil which remains trapped at residual saturation above and below the lens as the lens thickness decreases after the source has been cut-off. The right-hand-side in equation (40) gives the change in hydrocarbon volume within the cylinder. The radial flow component may be calculated from

37A

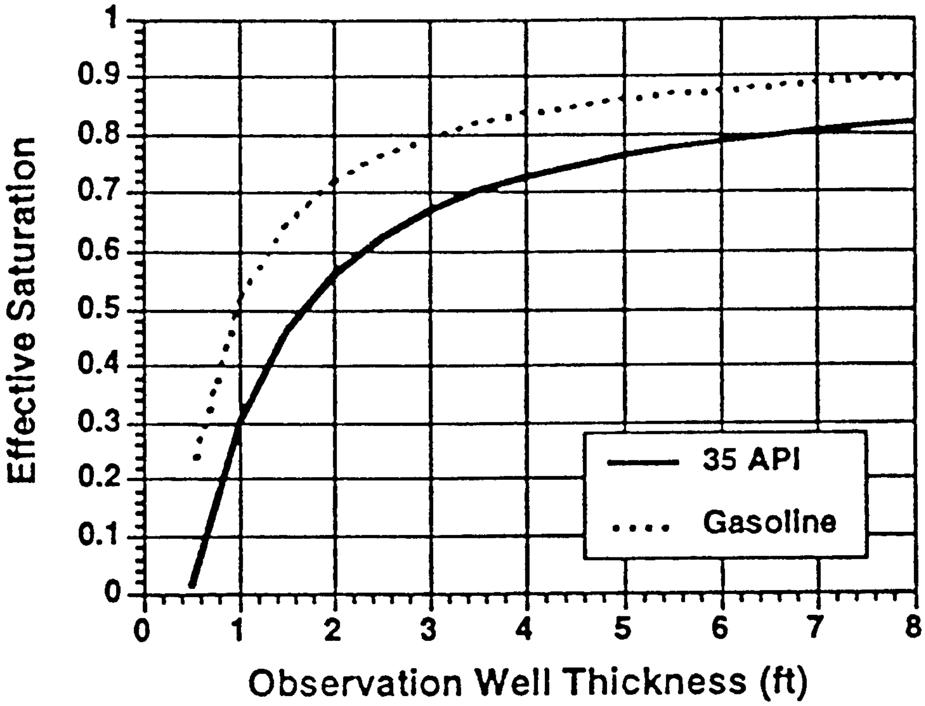

Figure 14 Effective saturation for a hydrocarbon in a sand soil

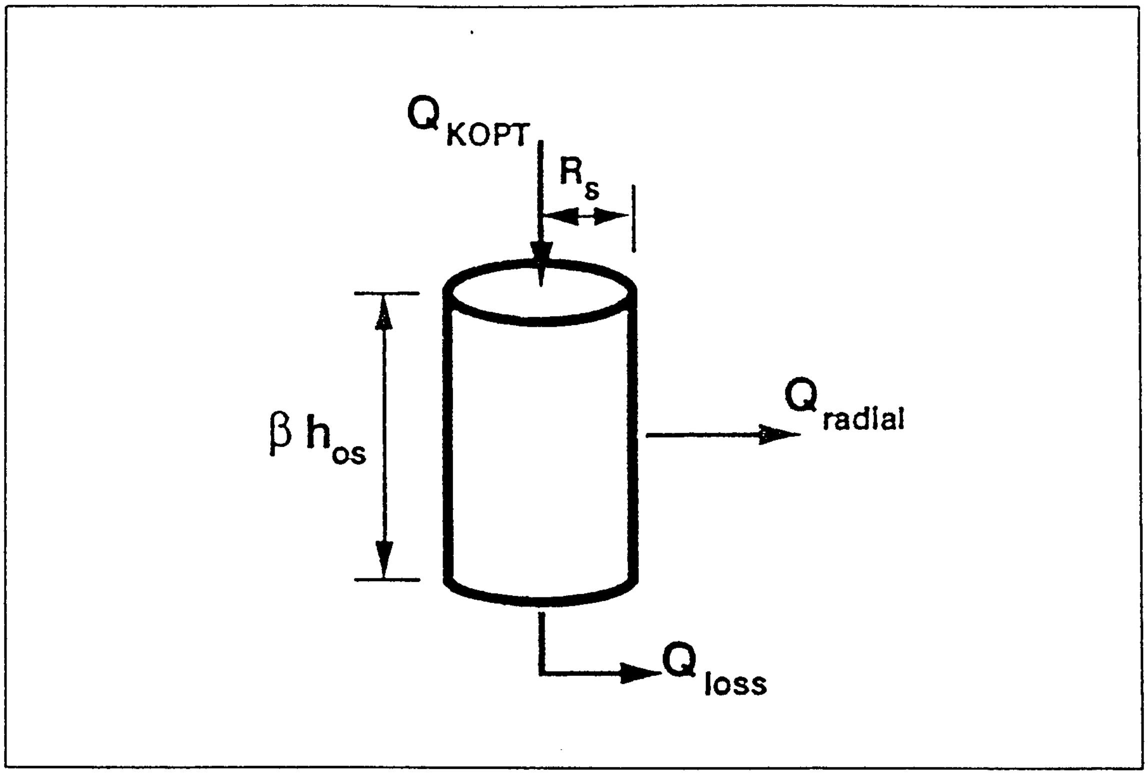

Figure 15 Volume balance for the source cylinder

$$Q_{radial} = -2\pi R_s b_o K_o \frac{dh_o}{dr}\Big|_{r=R_s} = \frac{\pi \beta K_o h_{os}^2}{\ln \frac{R_t}{R_s}} \qquad (41)$$

Equations (40) and (41), when combined with the discussion below for calculation of Q_{loss}, provide an ordinary differential equation for solving for the lens source head as a function of time:

$$\frac{dh_{os}}{dt} = F_1(h_{os}, R_t; Q_{KOPT}) \qquad (42)$$

In equation (42), h_{os} and R_t are functions which must be calculated and Q_{KOPT} is a function of time which is provided by the KOPT model.

The second equation for calculation of R_t comes from application of continuity to the lens as a whole. The continuity for the lens volume, V_L, may be written

$$\frac{dV_L}{dt} = Q_{KOPT} - Q_{out} \tag{43}$$

where Q_{out} represents the hydrocarbon losses from the lens due to dissolution as well as that left as residual during mound decay following source control. V_L includes only the actively spreading LNAPL. Since V_L is a function of h_{os} and R_t, we may use to chain rule to write

$$\frac{dV_L}{dt} = \frac{\partial V_L}{\partial h_{os}} \frac{dh_{os}}{dt} + \frac{\partial V_L}{\partial R_t} \frac{dR_t}{dt} \tag{44}$$

when combined with equation (43) this equation gives

$$\frac{dR_t}{dt} = \frac{Q_{KOPT} - Q_{out} - \dfrac{\partial V_L}{\partial h_{os}} \dfrac{dh_{os}}{dt}}{\dfrac{\partial V_L}{\partial R_t}} \tag{45}$$

The lens volume, V_L, is given by (see Appendix 1, ?)

$$V_L = \frac{\pi R_t^2 \theta_o \beta h_{os} \sqrt{\dfrac{\pi}{4}}\, erf\left(\sqrt{\ln\left(\dfrac{R_t}{R_s}\right)^2}\right)}{\sqrt{\ln\left(\dfrac{R_t}{R_s}\right)^2}} \tag{46}$$

In equation (46), erf( ) is the error function. With this equation the partial derivatives with respect to h_{os} and

R_t may be evaluated analytically. The resulting equation is

$$\frac{dR_t}{dt} = F_2\left(h_{os}, R_t, Q_{KOPT}\right) \tag{47}$$

Thus the lens model (equations (42) and (47)) gives a system of ordinary differential equations which are integrated with an ordinary differential equation solver. Since the KOPT model is also expressed as a system of ordinary differential equations, the two models are combined together in a single computer code. That code is called HSSM-KO, and is described in Volume 1 of the User's Guide (Weaver et. al., 1993).

Mass transfer of both the hydrocarbon and the chemical constituent from the oil lens to the aquifer occurs from infiltrating rainfall and dissolution caused by flowing groundwater. As the infiltrating rainfall moves through the lens it comes into chemical equilibrium with both the oil and the constituent, and the mass loss rate to the aquifer is

$$\dot{m}_{infil} = q_{wi}\, \pi\, R_t^2\, c_{wo} \tag{48}$$

where q_{wi} is the volume flux (Darcy velocity) of infiltrating rainfall and c_{wo} is the equilibrium concentration for water in contact with the hydrocarbon (see discussion below).

For dissolution it is assumed that the concentration of the contaminant at the base of the lens is equal to its equilibrium value in water. As the migrating groundwater within the aquifer approaches the lens it has no contaminant within it, and as the groundwater moves beneath the lens, the contaminant diffuses into the groundwater at a rate determined by continuity and vertical dispersion. This is essentially the model presented by Hunt et al. (1988). Let point x = 0 correspond to the upgradient edge of the lens with z being measured downward from the lens, and consider a column of groundwater which moves with velocity v beneath the lens. Then the continuity equation and boundary conditions for this moving column takes the form

$$v\frac{\partial c_w}{\partial x} = D_z\frac{\partial^2 c_w}{\partial z^2} \tag{49}$$

or with $D_z = a_v\, v$ where a_v is the vertical dispersivity,

$$\frac{\partial c_w}{\partial x} = a_v \frac{\partial^2 c_w}{\partial z^2} \tag{50}$$

with

$$\begin{aligned} c_w(z,0) &= 0 \\ c_w(0,x) &= c_{wo} \end{aligned} \tag{51}$$

where c_{wo} is the contaminant concentration within the water immediately beneath the lens. The solution is

$$c_w(z,x) = c_{wo}\, erfc\left(\frac{z}{\sqrt{4\, a_v x}}\right) \tag{52}$$

The plan view of the lens is shown in ~~7~~ 154. The total flux into the aquifer from the strip of width dy and of length L(y) is given by

$$\begin{aligned} \delta m(y) &= \int_0^{L(y)} - \eta\, D_z \frac{\partial c_w(0,x)}{\partial z}\, dx \\ &= 2\, c_{wo}\, \eta\, v \sqrt{\frac{a_v L(y)}{\pi}} \end{aligned} \tag{53}$$

The length, L(y), of the chord of the circle is

$$L(y) = 2\sqrt{R_t^2 - y^2} \tag{54}$$

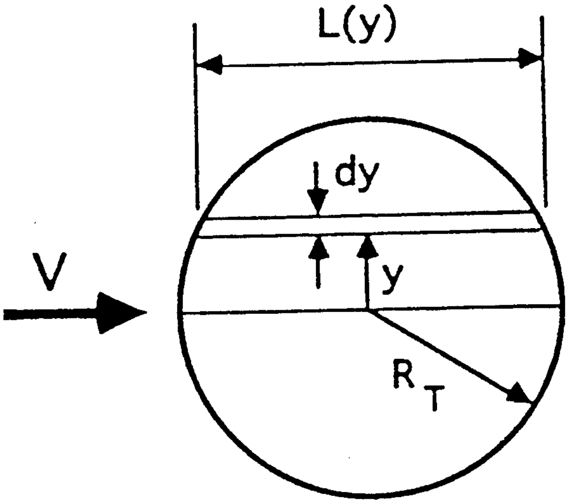

Figure 15A Plan view of the Oil Lens

so the total flux is given by

$$\begin{aligned} \dot{m}_{diss} &= 2\int_0^{R_t} \delta\, m(y)\, dy \\ &= 4\, c_{wo}\, \eta\, v R_t \sqrt{\frac{2 R_t a_v}{\pi}} \int_0^1 (1 - w^2)^{1/4}\, dw \end{aligned} \tag{55}$$

The integral in equation (55) may be evaluated numerically to give

$$I_d = \int_0^1 (1 - w^2)^{1/4}\, dw \cong 0.87402 \tag{56}$$

Thus the mass loss due to dissolution within the aquifer is

$$\dot{m}_{diss} = 4\, c_{wo}\, \eta\, v R_t I_d \sqrt{\frac{2 R_t a_v}{\pi}} \tag{57}$$

The groundwater source term is given by the sum of the m_{infil} and m_{diss} terms. Thus

$$\dot{m}_{source} = q_{wi}\, \pi\, R_t^2\, c_{wo} + 4\, c_{wo}\, \eta\, v R_t I_d \sqrt{\frac{2 R_t a_v}{\pi}} \tag{58}$$

It is apparent that the aquifer source term is dependent on the size of the lens, the infiltration rate and groundwater velocity, the constituent concentration within the lens, and the partitioning characteristics of the constituent between the oil and water.

The groundwater source term given by equation (58) requires an estimate of the equilibrium concentration in water in direct contact with the hydrocarbon, c_{wo}. This source term is derived from leaching of trapped hydrocarbon both above and below the lens, and from the spreading lens itself. The constituent mass continuity equations give the total mass, M_t, within the lens plus that trapped within the vadose and saturated zones. This total mass is related to the water equilibrium concentration through the partitioning relationships as follows:

$$M_t = \begin{pmatrix} (\theta_w + \theta_{orv} k_o + \rho_b k_d) V_{vz} + \\ ((\eta - \theta_o) + \theta_o k_o + \rho_b k_d) \dfrac{V_L}{\theta_o} + \\ ((\eta - \theta_{ors}) + \theta_{ors} k_o + \rho_b k_d) V_{sz} \end{pmatrix} c_{wo} \qquad (59)$$

In equation (59), V_{vz} and V_{sz} are the total volumes (LNAPL, water, and soil) containing residual hydrocarbon in the vadose and saturated zones, and V_L is the hydrocarbon volume in the spreading lens. These volumes are calculated as shown below. With M_t and the volumes known at any time, equation (59) provides the effective water concentration of the constituent.

It remains to determine the mass which remains behind with the hydrocarbon at residual saturation for a decaying lens after source control. The situation is shown in Figure 16. The lens continues to spread even if $dh_{os}/dt < 0$. The hydrocarbon and contaminant within the shaded region of Figure 16 becomes isolated from the lens with the hydrocarbon at residual saturation and the contaminant dissolved within the hydrocarbon and sorbed on the soil. Since the lens heights are the same at r = R for both times, equation (39) gives

$$\frac{\ln \dfrac{R_t(t+\Delta t)}{R}}{\ln \dfrac{R_t(t)}{R}} = \frac{h_{os}^2(t)}{h_{os}^2(t+\Delta t)} \; \frac{\ln \dfrac{R_t(t+\Delta t)}{R_s}}{\ln \dfrac{R_t(t)}{R_s}} = G \qquad (60)$$

where G is a constant and this equation is written for the lens radius and source height at times t and

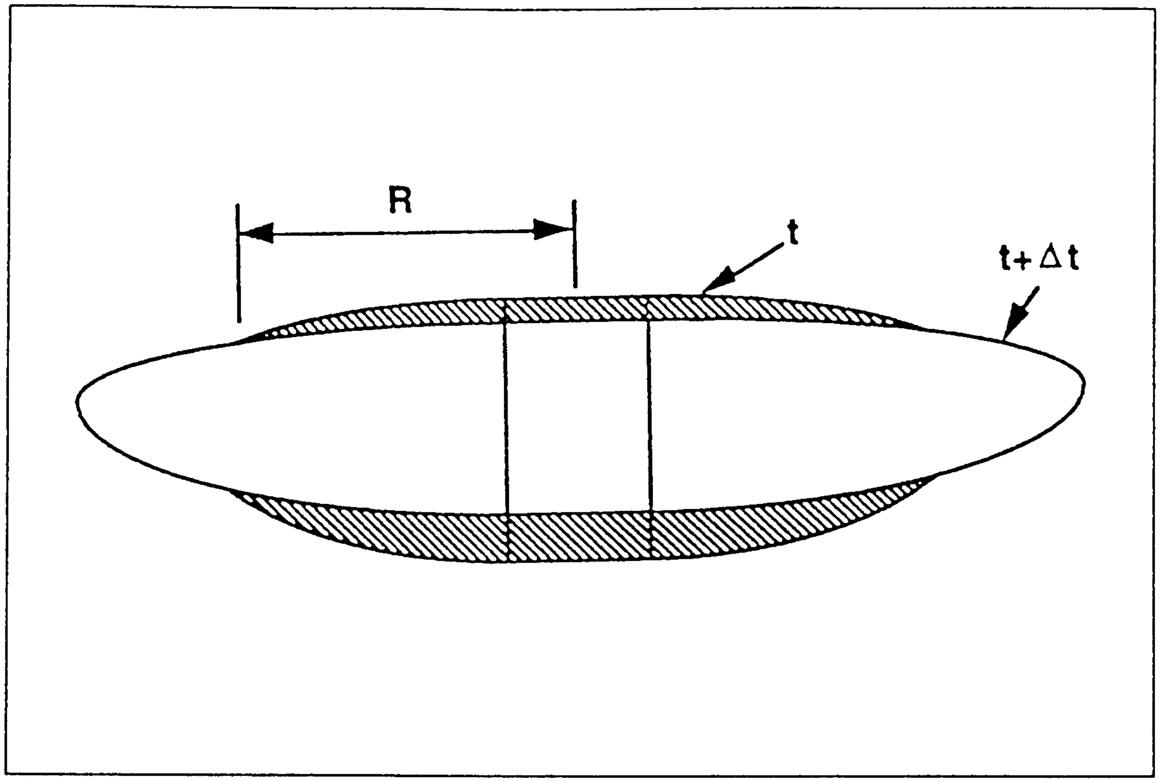

Figure 16 Residual volume for decaying mound

t+Δt. Since these are calculated from the model and are considered known at the end of time t+Δt, G is a known constant. We then have

$$\frac{R_t(t+\Delta t)}{R} = \left(\frac{R_t(t)}{R}\right)^G \tag{61}$$

or

$$R = \left(\frac{R_t(t)^G}{R_t(t+\Delta t)}\right)^{\frac{1}{G-1}} \tag{62}$$

With the radius R known from (62), the change in total volume occupied by residual hydrocarbon (LNAPL, water, and soil) may be found from equation (97) of Appendix 1, ?:

$$\Delta V_R = V_T(R; h_{os}(t), R_t(t)) - V_T(R; h_{os}(t + \Delta t), R_t(t + \Delta t)) \tag{63}$$

where it is understood that this is used only if $dh_{os}/dt < 0$. The fraction of the residual volume above the lens is 1/β and the fraction below the lens is (β-1)/β. Thus the volume of free product which becomes trapped during the time step is

$$\Delta V_L = \left(\frac{\theta_{orv}}{\beta} + \frac{\theta_{ors}(\beta - 1)}{\beta} \right) \Delta V_R \tag{64}$$

The corresponding mass loss is

$$\Delta M_L = c_o(t)\, \Delta V_L \tag{65}$$

The lens concentration is calculated from the ratio M_L/V_L, where M_L is the total constituent mass within the spreading lens.

SOURCE TERM CALCULATION ASSUMING FRESH JP-4
APPROXIMATE FREE-PRODUCT RADIUS (R_t) AT 1 YEAR = 5 FEET
AREA D
ELLSWORTH AIR FORCE BASE, SOUTH DAKOTA

Contaminant	Fuel-Water Partition Coefficient (K_{fw})[a/] [b/]	Weight Percent[a/]	Mass Fraction F_c (mg/Kg)	C_f (g/m^3)	C_{sat} (g/m^3)	Θ	q_{wi} (m/day)	V_a[c/] (m/day)	α_v[d/] (m)	R_t (m)	$M_{infil.}$ (g/day)	$M_{diss.}$ (g/day)	M_{total} (g/day)	M_{total} (mg/day)
Benzene	2.314E+02	5.00E-01	520.00	390.00	1.69	0.30	5.00E-04	0.12	5.49E-02	1.69	0.008	0.022	0.029	29.342
Toluene	8.949E+02	1.33E+00	350.00	262.50	0.29	0.30	5.00E-04	0.12	5.49E-02	1.69	0.001	0.004	0.005	5.107
Ethylbenzene	3.411E+03	3.70E-01	2200.00	1650.00	0.48	0.30	5.00E-04	0.12	5.49E-02	1.69	0.002	0.006	0.008	8.422
o-xylene	3.162E+03	1.01E+00	6000.00	4500.00	1.42	0.30	5.00E-04	0.12	5.49E-02	1.69	0.006	0.018	0.025	24.777
m-xylene	3.539E+03	9.60E-01	6000.00	4500.00	1.27	0.30	5.00E-04	0.12	5.49E-02	1.69	0.006	0.016	0.022	22.137
p-xylene	2.961E+03	3.50E-01	7000.00	5250.00	1.77	0.30	5.00E-04	0.12	5.49E-02	1.69	0.008	0.023	0.031	30.869
										Total	0.031	0.090	0.121	120.654

[a/] Martel, 1987

[b/] Smith and others, 1981

[c/] Velocity estimated in Section 3 of report.

[d/] Estimated at 1/200 of the longitudinal dispersivity estimate (Section 6).

C_f = Concentration in fuel = $F_m \rho_{JP-4}$
ρ_{JP-4} = .75gm/cm^3
C_{sat} = Saturation Concentration = C_f/K_{fw}
Θ = porosity
q_{wi} = estimated precipitation infiltration rate (m/day)
α_v = Vertical dispersivity, m. 3.33E-02
V_a = Average groundwater velocity, m/day.
R_t = Radius of LNAPL plume.
$M_{diss.}$ and $M_{infil.}$ estimated from Charbeneau & Weaver (1993).
$M_{diss.}$ = Mass loss rate from dissolution at groundwater/LNAPL interface, g/d
$= C_{sat}\Theta V_a R_t I_d (2R_t \alpha_v / \pi)^{0.5}$
$M_{infil.}$ = Mass loss rate from infiltrating precipitation, g/d
$= q_{wi} \pi R_t^2 C_{sat}$
Id ~ 0.87402
$M_{total} = M_{diss.} + M_{infil.}$, g/d

SOURCE TERM CALCULATION ASSUMING FRESH JP-4
APPROXIMATE FREE-PRODUCT RADIUS (R_t) AT 1 YEAR = 3.75 FEET
(25% REDUCTION DUE TO BIOSLURPING/BIOVENTING)
AREA D, ELLSWORTH AIR FORCE BASE, SOUTH DAKOTA

Contaminant	Fuel-Water Partition Coefficient (K_{fw})[a/] [b/]	Weight Percent[a/]	Mass Fraction F_c (mg/Kg)	C_f (g/m^3)	C_{sat} (g/m^3)	Θ	q_{wi} (m/day)	V_a[c/] (m/day)	α_v[d/] (m)	R_t (m)	$M_{infil.}$ (g/day)	$M_{diss.}$ (g/day)	M_{total} (g/day)	M_{total} (mg/day)
Benzene	2.314E+02	5.00E-01	520.00	390.00	1.69	0.30	5.00E-04	0.12	5.49E-02	1.14	0.003	0.012	0.016	15.508
Toluene	8.949E+02	1.33E+00	350.00	262.50	0.29	0.30	5.00E-04	0.12	5.49E-02	1.14	0.001	0.002	0.003	2.699
Ethylbenzene	3.411E+03	3.70E-01	2200.00	1650.00	0.48	0.30	5.00E-04	0.12	5.49E-02	1.14	0.001	0.003	0.004	4.451
o-xylene	3.162E+03	1.01E+00	6000.00	4500.00	1.42	0.30	5.00E-04	0.12	5.49E-02	1.14	0.003	0.010	0.013	13.095
m-xylene	3.539E+03	9.60E-01	6000.00	4500.00	1.27	0.30	5.00E-04	0.12	5.49E-02	1.14	0.003	0.009	0.012	11.700
p-xylene	2.961E+03	3.50E-01	7000.00	5250.00	1.77	0.30	5.00E-04	0.12	5.49E-02	1.14	0.004	0.013	0.016	16.314
										Total	0.014	0.050	0.064	63.767

[a/] Martel, 1987

[b/] Smith and others, 1981

[c/] Velocity estimated in Section 3 of report.

[d/] Estimated at 1/200 of the longitudinal dispersivity estimate (Section 6).

C_f = Concentration in fuel = $F_m \rho_{JP-4}$

ρ_{JP-4} = .75gm/cm^3

C_{sat} = Saturation Concentration = C_f/K_{fw}

Θ = porosity

q_{wi} = estimated precipitation infiltration rate (m/day)

α_v = Vertical dispersivity, 3.33E-02

V_a = Average groundwater velocity, m/day.

R_t = Radius of LNAPL plume.

$M_{diss.}$ and $M_{infil.}$ estimated from Charbeneau & Weaver (1993).

$M_{diss.}$ = Mass loss rate from dissolution at groundwater/LNAPL interface, g/d

$= C_{sat}\Theta V_a R_t I_d (2R_t\alpha_v/\pi)^{0.5}$

M_{infil} = Mass loss rate from infiltrating precipitation, g/d

$= q_{wi}\pi R_t^2 C_{sat}$

Id ~ 0.87402

$M_{total} = M_{diss.} + M_{infil.}$, g/d

SOURCE TERM CALCULATION ASSUMING FRESH JP-4
APPROXIMATE FREE-PRODUCT RADIUS (R_t) AT 2 YEAR = 2.5 FEET
(ADDITIONAL 25% REDUCTION DUE TO BIOSLURPING/BIOVENTING)
AREA D, ELLSWORTH AIR FORCE BASE, SOUTH DAKOTA

Contaminant	Fuel-Water Partition Coefficient (K_{fw})[a/][b/]	Weight Percent[a/]	Mass Fraction F_c (mg/Kg)	C_f (g/m^3)	C_{sat} (g/m^3)	Θ	q_{wi} (m/day)	V_a[c/] (m/day)	α_v[d/] (m)	R_t (m)	$M_{infil.}$ (g/day)	$M_{diss.}$ (g/day)	M_{total} (g/day)	M_{total} (mg/day)
Benzene	2.314E+02	5.00E-01	520.00	390.00	1.69	0.30	5.00E-04	0.12	5.49E-02	0.76	0.002	0.007	0.008	8.098
Toluene	8.949E+02	1.33E+00	350.00	262.50	0.29	0.30	5.00E-04	0.12	5.49E-02	0.76	0.000	0.001	0.001	1.409
Ethylbenzene	3.411E+03	3.70E-01	2200.00	1650.00	0.48	0.30	5.00E-04	0.12	5.49E-02	0.76	0.000	0.002	0.002	2.324
o-xylene	3.162E+03	1.01E+00	6000.00	4500.00	1.42	0.30	5.00E-04	0.12	5.49E-02	0.76	0.001	0.006	0.007	6.838
m-xylene	3.539E+03	9.60E-01	6000.00	4500.00	1.27	0.30	5.00E-04	0.12	5.49E-02	0.76	0.001	0.005	0.006	6.109
p-xylene	2.961E+03	3.50E-01	7000.00	5250.00	1.77	0.30	5.00E-04	0.12	5.49E-02	0.76	0.002	0.007	0.009	8.519
										Total	0.006	0.027	0.033	33.297

[a/] Martel, 1987

[b/] Smith and others, 1981

[c/] Velocity estimated in Section 3 of report.

[d/] Estimated at 1/200 of the longitudinal dispersivity estimate (Section 6).

C_f = Concentration in fuel = $F_m \rho_{JP-4}$

ρ_{JP-4} = .75gm/cm^3

C_{sat} = Saturation Concentration = C_f/K_{fw}

Θ = porosity

q_{wi} = estimated precipitation infiltration rate (m/day)

α_v = Vertical dispersivity, 3.33E-02

V_a = Average groundwater velocity, m/day.

R_t = Radius of LNAPL plume.

$M_{diss.}$ and $M_{infil.}$ estimated from Charbeneau & Weaver (1993).

$M_{diss.}$ = Mass loss rate from dissolution at groundwater/LNAPL interface, g/d

$= C_{sat}\Theta V_a R_t I_d (2R_t\alpha_v/\pi)^{0.5}$

$M_{infil.}$ = Mass loss rate from infiltrating precipitation, g/d

$= q_{wi}\pi R_t^2 C_{sat}$

Id ~ 0.87402

$M_{total} = M_{diss.} + M_{infil.}$, g/d

Example Calculation for Weathering
LNAPL Source Term
Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, SD

At Time = 0, total mass of BTEX = 22,070 mg/kg
(based on LNAPL analytical results)

⇒ Using OILENS, mass of total BTEX that can dissociate into underlying groundwater is 90 mg/day
(see spreadsheet @ 1 yr)

⇒ Based on this mass removal rate, the LNAPL source would be reduced by 16% or 3,735 mg/kg in the first year.
(based on mass removed in 365 days + resultant reduction in source mass total)

⇒ Remaining mass of total BTEX = 18,335 mg/kg

At Time = 1 year then, OILENS calculates that mass of total BTEX that can dissociate is reduced to 60 mg/day

Table 6.4 presents the iterative weathering results using this method

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Similar calculation used to simulate impacts to source term after reduce radii of LNAPL using bioslurping. Same approach, but refer to reduced LNAPL area spreadsheets for starting total BTEX mass @ years 1 + 2

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REGRESSION TECHNIQUES AND ANALYTICAL SOLUTIONS TO DEMONSTRATE INTRINSIC BIOREMEDIATION

Timothy E. Buscheck and Celia M. Alcantar
Chevron Research and Technology Company
Richmond, CA

ABSTRACT

It is now generally recognized that a major factor responsible for the attenuation and mass reduction of benzene, toluene, ethylbenzene, and xylenes (BTEX) in groundwater plumes is hydrocarbon biodegradation by indigenous microorganisms in aquifer material. Our objective is to apply well-known regression techniques and analytical solutions to estimate the contribution of advection, dispersion, sorption, and biodecay to the overall attenuation of petroleum hydrocarbons. These calculations yield an apparent biodecay rate based on field data. This biodecay rate is a significant portion of the overall attenuation in stable, dissolved hydrocarbon plumes.

INTRODUCTION

"Intrinsic bioremediation" is the degradation of organic compounds by indigenous microbes without artificial enhancement. Advection, dispersion, sorption, and decay each contribute to the overall attenuation of a dissolved hydrocarbon plume. The effect of advection is to transport dissolved contaminants at the same rate as the groundwater velocity. The effect of dispersion is to spread contaminant mass beyond the volume it would occupy due to advection alone, and reduce contaminant concentrations. The effect of sorption is to retard contaminant migration. These factors affect the configuration of dissolved hydrocarbon plumes. Overall attenuation can cause a plume to shrink over time, create a stable plume, or reduce the rate of plume migration. Two of the conditions for which intrinsic bioremediation is likely to contribute to the configuration of a contaminant plume are a shrinking plume and a stable plume. The configuration of a migrating plume can also be affected by intrinsic bioremediation. Under the conditions of a shrinking plume, degradation mechanisms are necessarily present. Intrinsic bioremediation also is likely to contribute to a stable plume, particularly if the source persists in residually contaminated soils at the water table. In this paper we couple the regression of concentration versus distance for stable plumes to an analytical solution for one-dimensional, steady-state, contaminant transport. The analytical solution includes advection, dispersion, sorption, and decay.

Biological transformation is the process that likely contributes most to the decay of compounds such as BTEX. Several studies suggest the concurrent loss of electron acceptors from groundwater as an indicator of biodegradation (McAllister and Chiang 1994, Salanitro 1993). The mechanism of biodegradation is complex, and the rate is most likely controlled by the mixing of the contaminant and electron acceptors in a three-dimensional, heterogeneous aquifer. The assumption of a first-order decay is a useful approximation of this complex phenomenon. Evaluation of site data suggests apparent first-order attenuation rates occur in the range of 0.1 to 1.0 % per day (Buscheck et al. 1993).

The objective of this paper is to provide tools to assist in documenting the loss of contaminants. The regression techniques and analytical solution described are intended to distinguish those mechanisms that contribute to contaminant loss.

PLUME CHARACTERISTICS

Shrinking Plume

Dissolved hydrocarbon plumes may decrease in size, as observed by declining contaminant concentrations in monitoring wells. Exponential regression methods can be used to evaluate whether concentration versus time data fit a first-order decay observed for petroleum hydrocarbons under certain conditions. The solution to the first-order decay is:

$$C(t) = C_i e^{-(kt)} \tag{1}$$

Where C(t) (M/L^3) is concentration as a function of time, t (T), C_i is the initial concentration at $t = 0$, and k is the first-order attenuation rate, T^{-1}. Equation (1) may be used to evaluate contaminant concentration versus time data for individual monitoring wells.

Stable Plume

A stable plume is characterized by dissolved contaminant concentrations remaining constant over time in individual monitoring wells. Short-term variations in monitoring well concentrations due to water table fluctuation, variability in groundwater flow direction, sampling variability, and analytical uncertainty should be distinguished from statistically significant concentration changes. In order for a plume to reach stable conditions, the rate of natural attenuation must be equal to the rate of contaminant addition to the aquifer from the source (McAllister and Chiang 1994). The contaminant source or influx rate is limited by the compound's effective solubility and the flow rate of water through the source area (infiltration, fluctuating water table, etc.).

Kemblowski et al. (1987) recast equation (1) for concentration as a function of distance:

$$C(x) = C_o e^{-(k \frac{x}{v_x})} \tag{2}$$

Where C_o (M/L^3) is the concentration at the source. The transformation of the exponential terms in equations (1) and (2) is achieved by substituting time, t, with distance traveled, x (L) divided by the linear groundwater velocity, v_x (L/T). The term "x/v_x" is the residence time for pore water to move some distance, x, from the source. The concentration versus distance regression is based on equation (2). The groundwater flow direction is defined based on multiple monitoring events covering the hydrologic cycle. Six monitoring wells were selected along the groundwater flow path (see inset of Figure 1). A minimum of three monitoring wells are required for this analysis. In this case, contaminant concentrations declined with downgradient distance. Figure 1 plots benzene concentration versus distance for a terminal in Fairfax, Virginia. From the exponent of equation (2), the slope of the line in Figure 1 is k/v_x (L^{-1}), the reciprocal of the attenuation distance. If this slope is multiplied by groundwater velocity (L/T), we obtain k (T^{-1}). In the absence of a reliable estimate of groundwater velocity, the k/v_x term is useful, particularly for estimating the downgradient extent of contaminant migration and selecting downgradient monitoring well locations.

ANALYTICAL SOLUTION FOR A STABLE PLUME

The general one-dimensional transport equation, with first-order decay of the contaminant, is given by the following equation:

$$\frac{\delta C}{\delta t} = \frac{1}{R_f} [D_x \frac{\delta^2 C}{\delta x^2} - v_x \frac{\delta C}{\delta x}] - \lambda C \qquad (3)$$

Where D_x (L^2/T) is the dispersion coefficient, v_x (L/T) is the linear groundwater velocity, R_f (-) is the retardation coefficient, and λ (T^{-1}) is the total decay rate. The form of equation (3) assumes D_x is constant and independent of distance, x. While the terms in brackets describe the mass transport by dispersion and advection, respectively, the retardation coefficient characterizes the contribution of sorption. The form of this equation assumes degradation occurs in the aqueous and sorbed phases at the same rate. If biological transformation of BTEX compounds occurs primarily in the aqueous phase, the term "λC" would appear inside the brackets.

Dispersion and advection are related by the longitudinal dispersivity, α_x (L), which has been described by empirical expressions (Fetter 1993).

$$D_x = \alpha_x v_x \qquad (4)$$

The retardation coefficient (R_f) accounts for contaminant partitioning between the solid and aqueous phases. R_f describes the relationship between the linear groundwater velocity, and contaminant velocity, v_c (L/T):

$$R_f = \frac{v_x}{v_c} \qquad (5)$$

Chiang et al. (1989) demonstrated that the contribution of volatilization to the dissolved contaminant attenuation was only 5% at one site. Except in the case of very shallow groundwater, volatilization is not expected to contribute significantly to the overall attenuation. Therefore, volatilization is neglected and the decay rate is assumed to be a measure of biodegradation of BTEX compounds.

Bear (1979) solved equation (3) for concentration. The steady-state solution is given as:

$$C(x) = C_o \exp [(\frac{x}{2\alpha_x}) [1 - (1 + \frac{4\lambda\alpha_x}{v_c})^{\frac{1}{2}}]] \qquad (6)$$

For the case in which decay occurs only in the aqueous phase, the contaminant velocity, v_c, is replaced by the linear groundwater velocity, v_x, in equation (6). As the decay rate (λ) increases with respect to the other transport mechanisms, the concentration away from the source ($x > 0$), approaches zero because the material is decaying at a greater rate than it is being transported through the medium. Similarly, as the contaminant velocity increases, the decay becomes less effective in reducing concentrations as a function of distance. Retarded contaminants therefore have a greater opportunity to decay because retarded transport velocities favor biodegradation kinetics over transport (Domenico and Schwartz 1990).

The exponential regression for concentration versus distance yields the reciprocal of the attenuation distance, k/v_x (L^{-1}), previously shown in equation (2). Equations (2) and (6) are of the same form:

$$C(x) = C_o \exp(mx) \tag{7}$$

The slope of the log-linear data is given by m. The one-dimensional, steady-state transport solution also describes the slope, m, of the log-linear data:

$$m = \left(\frac{1}{2\alpha_x}\right) \left[1-\left(1+\frac{4\lambda\alpha_x}{v_c}\right)^{\frac{1}{2}}\right] \tag{8}$$

Therefore, the term k/v_x and equation (8) both describe the slope of the log-linear data and can be equated to solve for the total decay rate, λ, a measure of intrinsic bioremediation. Dispersivity (α), contaminant velocity (v_c), and k/v_x are input to the following equation to calculate the decay rate.

$$\lambda = \left(\frac{v_c}{4\alpha_x}\right) \left(\left[1+2\alpha_x\left(\frac{k}{v_x}\right)\right]^2 - 1\right) \tag{9}$$

For the case in which decay occurs only in the aqueous phase, v_c is replaced by v_x in equation (9).

RESULTS

The results of equating the spatial regression with the steady-state analytical solution for the Fairfax Terminal are presented in Table 1. The values for source concentration (C_o) and k/v_x were regressed using the data plotted in Figure 1. Table 1 includes k and the ratio, λ/k, the contribution of biodecay to the overall attenuation rate (expressed as %). In Case 1, groundwater velocity was 0.06 m/day, based on aquifer pump tests. Retardation was estimated as 2 and dispersivity was estimated as 7.5 m, approximately 5% of the flow field (distance separating the two furthest wells). In Case 1, λ = 0.30%/day (0.0030 days^{-1}); λ is 75% of k for this case. The next four cases were performed to evaluate the sensitivity of changing various input parameters. In each of these cases C_o and k/v_x remain constant. In Case 2, the groundwater velocity is reduced by a factor of two (v = 0.03 m/day), which reduces the decay rate by the same factor (λ = 0.15%/day). In this case, only half the decay rate is required to maintain the Case 1 concentration decline with distance; as in Case 1, λ is 75% of k in Case 2. In Case 3, the dispersivity is increased by a factor of two (α = 15 m) and λ = 0.40%/day. More decay is required with a larger dispersivity because more spreading of the contaminant occurs in the direction of groundwater flow; λ is equivalent to k in Case 3.

Cases 4 and 5 were performed to calculate λ assuming biodecay occurs only in the aqueous phase. This is accomplished by replacing v_c with v_x in equation (9) for λ (R = 1 in Table 1 for Cases 4 and 5). Given this revised formulation, the decay rate, λ, is independent of retardation. By limiting decay to the aqueous phase in Case 4, λ = 0.60%/day, twice the decay rate in Case 1. In Case 4, λ is 150% of k. Case 5 is similar to Case 4, but dispersivity is reduced to 0.3 m. In Case 5, λ = 0.40%/day. Less decay is required with a smaller dispersivity because less spreading of the contaminant plume occurs in the direction of groundwater flow; λ and k are identical in Case 5.

SUMMARY

Contaminant decay is the primary process contributing to a stable configuration of a dissolved contaminant plume. Given a constant source, sorption and dispersion alone are not likely to account for a stable plume. Sorption only retards contaminant velocity, whereas dispersion results in further spreading of the contaminant, reducing concentrations. Decay (biodegradation of BTEX compounds) is the most significant mechanism that accounts for mass loss in a dissolved contaminant plume. The analytical solution for steady-state contaminant transport can be equated to a regression of concentration versus distance (expressed as k/v_x) to solve for the decay rate, λ. The decay rate is a measure of intrinsic bioremediation of petroleum hydrocarbons and can be used in more sophisticated models.

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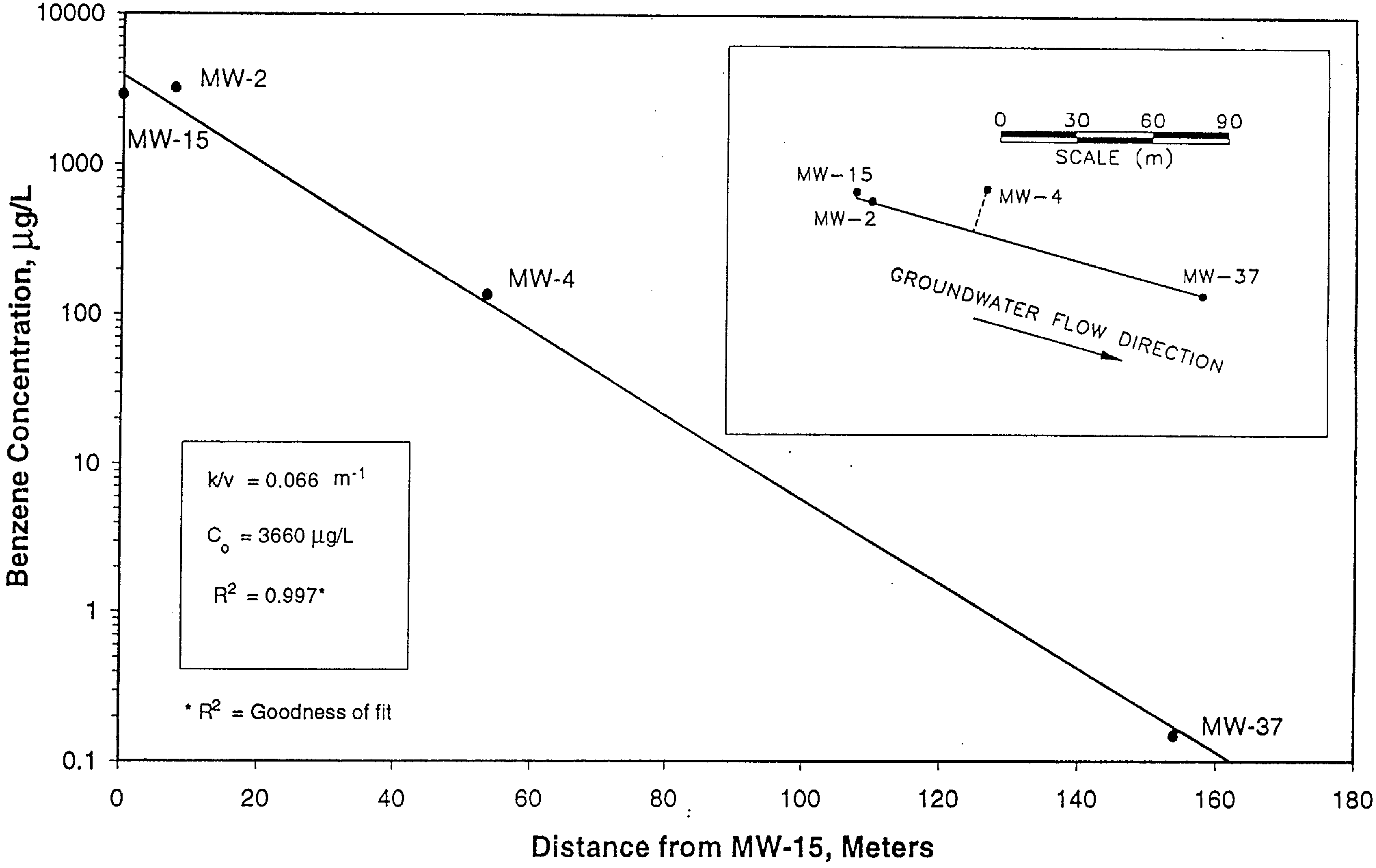

FIGURE 1. Exponential regression of concentration versus distance for Fairfax Terminal.

TABLE 1. Decay rates based on steady-state analytical solution, C_o = 3,660 μg/L, k/v_x = 0.066 m^{-1}. (sensitivity on bold input values)

Case	groundwater velocity, v_x (m/day)	retardation coefficient, R_f	contaminant velocity, v_c (m/day)	dispersivity, α (m)	attenuation rate, k (%/day)	decay rate, λ (%/day)	λ/k (%)
Case 1	0.06	2	0.03	7.5	0.40	0.30	75
Case 2	**0.03**	2	0.015	7.5	0.20	0.15	75
Case 3	0.06	2	0.03	**15**	0.40	0.40	100
Case 4	0.06	**1**(1)	0.06	7.5	0.40	0.60	150
Case 5	0.06	**1**(1)	0.06	**0.3**	0.40	0.40	100

Note: (1) Calculation of λ independent of v_c.

BIOPLUME II MODEL SETUP AND RESULTS

Overview and Model Description

To help estimate how dissolved BTEX compounds will migrate in groundwater at Area D under the influence of natural chemical attenuation processes, .Parsons ES used a quantitative numerical groundwater flow and contaminant transport model that provides for *in situ* degradation of contaminant mass. The modeling effort was conducted as part of the risk-based remedial evaluation process to identify the contaminant mass and concentration that would be expected to persist in impacted media over time and to assess whether potential exposure pathways involving groundwater could be completed. The numerical model was developed using site-specific data and conservative assumptions about governing physical and chemical processes. Due to the conservative nature of the model input, the reduction in contaminant mass resulting from natural attenuation processes are expected to exceed model predictions.

The Bioplume II code was used to estimate the nature and extent of BTEX migration in groundwater at Area D accounting for the effects of natural chemical attenuation mechanisms on contaminant mass, concentration, mobility, persistence, and toxicity. The Bioplume II model incorporates advection, dispersion, sorption, and biodegradation to simulate contaminant plume migration and degradation. The model is based upon the USGS Method of Characteristics (MOC) two-dimensional (2-D) solute transport model of Konikow and Bredehoeft (1978). The model was modified by researchers at Rice University to include a biodegradation component that can be activated by a superimposed dissolved oxygen (DO) plume. Based on the work of Borden and Bedient (1986), the model assumes a reaction between DO and BTEX mass that is instantaneous relative to the advective groundwater velocity. Bioplume II solves the USGS 2-D solute transport equation twice, once for total BTEX concentrations in the aquifer and once for a DO plume. The two plumes are combined using superposition at every particle move to simulate the instantaneous, biologically-mediated reaction between total BTEX and DO.

It has become apparent that anaerobic processes such as denitrification or nitrate reduction, manganese reduction, ferric iron reduction, sulfate reduction, and methanogenesis can be important BTEX degradation mechanisms (Grbic′-Galic′, 1990; Beller *et al.*, 1992; Edwards *et al.*, 1992; Edwards and Grbic′-Galic′, 1992; Grbic′-Galic′ and Vogel, 1987; Lovley *et al.*, 1989; Hutchins, 1991). Reliance on DO-activated degradation in the numerical model may severely underestimate the effects of natural chemical attenuation processes on contaminant mass, concentration, and mobility over time. To account for these substantial destructive chemical attenuation processes in model simulations, it also is possible to simulate both ananerobic and aerobic contaminant degradation in Bioplume II using a site-specific decay constant. This was the modeling approach pursued for Area D because the site-specific geochemical evidence discussed in Section 6 suggests that anaerobic biodegradation of BTEX compounds is occurring at the site via manganese reduction, ferric iron reduction, sulfate reduction, and possibly methanogenesis at the source area. By basing the decay constant on site-specific data and observed chemical attenuation at the field scale, the numerical model accounts for the limiting effects of mass transfer, mixing, and degradation kinetics on contaminant mass loss estimates. The following subsections discuss this approach and other model input parameters, model assumptions, model calibration, and the simulation results in further detail.

Conceptual Model Design and Assumptions

Prior to developing a groundwater model, it is important to determine if sufficient data are available to provide a reasonable estimate of aquifer conditions. In addition, it is important to ensure that any limiting assumptions can be justified. Data and information presented in Section 6 suggest that at least oxygen, manganese, ferric iron, and sulfate are being used as electron acceptors during both aerobic and anaerobic biodegradation of fuel hydrocarbons. As discussed previously, the combined effect of these chemical decay processes is incorporated into the model through use of a site-specific decay constant.

Based on the data presented in Section 3, the shallow saturated zone was conceptualized and modeled as a shallow unconfined aquifer composed of gravels, sands, silts, and clays all overlying fractured bedrock (Figures 3.3 and 3.4). The saturated thickness of the aquifer is estimated to vary from below 1 foot to approximately 6 feet in thickness. Saturated thickness varies significantly over the site as a result of a paleochannel running to the southeast from the source area at Area D. In addition, occasional pockets of silty and clayey sands and fractured bedrock apparently affect groundwater flow direction and hydraulics. Based on the estimated potentiometric surface at the site, groundwater appears to flow from the source area to the northeast toward a large bowl-shaped depression beneath the fuel yard and adjacent to the site. This bowl shaped depression is a result of decreased bedrock elevations.

However, field data suggest that groundwater flows more readily through the unconsolidated gravel layer resting on the shale. This means that a preferential flow or channel may be present through the suspected source area, through MW-17, and beyond, toward MW-29. The presence of this channel, which apparently encourages preferential contaminant flow and transport, explains why dissolved fuel hydrocarbons flow to the northeast (in the direction of the groundwater gradient) away from the suspected source area, and then takes a sharp turn toward the southeast. These hydrogeologic characteristics are described more fully in Sections 3 and 4.

Because of the potential presence of these preferential contaminant transport channels, the Bioplume II model was used to estimate the maximum travel distance by concentration from the source area expected at the site. The model results presented in Section 6 and Section 8 show how far dissolved BTEX could travel in these preferential channels, where the groundwater velocity reaches its maximum. This modeling approach is conservative because it assumes that contaminant mass is migrating under the worst-case conditions possible at this particular site. Parsons ES opted to pursue this approach, however, to estimate how far dissolved contamination could travel in groundwater, particularly in the direction of areas that are not placed under extensive exposure controls. As noted before, however, this approach and the subsequent model results are likely to overestimate the extent of migration and underestimate the beneficial effects of chemical attenuation processes that will actually be observed at the site over time.

The use of a 2-D model is appropriate at Area D because the saturated interval is thin, and the local flow system, as defined by groundwater elevation data and the deep, underlying Pierre Shale year (estimated at 860 feet thick), will likely prevent significant downward vertical migration of dissolved BTEX contamination. The approximate source of JP-4 contamination at the site is identified, and is located adjacent to the JP-4 dispensers and USTs near Building 8215 at the site. Contaminated soils at the site have not been fully remediated, although a pilot bioventing system has been operating for more than a year near the suspected source area. Additionally, LNAPL contamination may still exist. However, no LNAPL was encountered at this site during the 1994 field investigation. Pockets of residual fuel hydrocarbon contamination may also exist, but were not included as a potential source to groundwater because of the low precipitation infiltration rates expected at this site (Section 6). To develop conservative model predictions, a continuing source factor from mobile LNAPL was incorporated into the Bioplume II model for this site to account for the possible additional dissolution of BTEX into groundwater over time. The calculations used to derive the source term for this model are summarized in Section 6, and fully presented elsewhere in this appendix.

Initial Model Setup

Where possible, the initial setup for this model was based on site-specific data. Where site-specific data were not available (e.g., effective porosity), reasonable assumptions for the types of materials comprising the shallow aquifer were made based on widely-accepted literature values. The following sections describe the basic model setup.

Grid Design and Boundary Conditions

The maximum grid size for the Bioplume II model is limited to 20 columns by 30 rows. The dimension of each column and row can range from 0.1 to 999.9 feet. A 20- by 30-cell grid was used to model Area D. Each grid cell was 45 feet long by 45 feet wide. The grid was oriented so that the longest dimension was parallel to the overall direction of groundwater flow. The grid encompasses the existing BTEX plume with sufficient space between all model boundaries to avoid significant numerical errors caused by contact between the boundary and the BTEX plume. The model grid covers an area of 1,215,000 square feet, or approximately 28 acres. The full extent of the model grid is indicated on Figure 1.

Model boundaries are mathematical statements that represent hydrogeologic boundaries, such as areas of specified head (i.e., surface water bodies or contour lines of constant hydraulic head) or specified flux. Hydrogeologic boundaries are represented by three mathematical statements that describe the hydraulic head at the model boundaries. These include:

- Specified-head boundaries (Dirichlet condition) for which the head is determined as a function of location and time only. Surface water bodies exhibit constant head conditions. Specified-head boundaries are expressed mathematically as:

  $$Head = f(x,y,z,t)$$

  where f is the function symbol, x, y, and z are position coordinates, and t is time.

- Specified-flow boundaries (Neumann conditions) for which the mathematical description of the flux across the boundary is given. The flux is defined as a volumetric flow rate per unit area (i.e., $ft^3/ft^2/day$). No-flow boundaries are a special type of specified flow boundary and are set by specifying the flux to be zero. Examples of no-flow boundaries include groundwater divides and impermeable hydrostratigraphic units. Specified-flux boundaries are expressed mathematically as:

  $$Flux = f(x,y,z,t)$$

- 3) Head-dependent flow boundaries (Cauchy or mixed-boundary conditions) where the flux across the boundary is calculated from a given boundary head value. This type of flow boundary is sometimes referred to as a mixed-boundary condition because it is a combination of a specified-head boundary and a specified-flow boundary. Head-dependent flow boundaries are used to model leakage across semipermeable boundaries. Head-dependent flow boundaries are expressed mathematically as (Bear, 1979):

$$Flux = \frac{(H_0 - H)K'}{B'}$$

Where: H = Head in the zone being modeled (generally the zone containing the contaminant plume)

H_0 = Head in external zone (separated from plume by semipermeable layer)

K' = Hydraulic conductivity of semipermeable layer

B' = Thickness of semipermeable layer.

Natural hydraulic boundaries are modeled using a combination of the three types of model boundary conditions listed above. When possible, hydrologic boundaries such as surface water bodies, groundwater divides, contour lines, or hydrologic barriers should coincide with the perimeter of the model. In areas lacking obvious hydrologic boundaries, specified-head or specified-flux boundaries can be specified at the model perimeter if the boundaries are far enough removed from the contaminant plume that transport calculations are not affected. Bioplume II requires the entire model domain to be bounded by zero-flux cells (also known as no-flow cells), with other boundary conditions established within the subdomain specified by the no-flow cells.

Specified-head boundaries for the model were set on the southwest and northeast perimeter of the model grid to simulate groundwater flow to the northeast as observed at the site. The head of the southwest model boundary (135 feet southwest of the source) was estimated to be between 3228.0 and 3225.0 feet above msl. The heads at the southwest boundary varied significantly as a result of bedrock topography upgradient of the source area. The northeast model (990 feet northeast of the source) was estimated to be 3225.0 to 3225.8 feet above msl.

The northwest and southeast model boundaries were configured as no-flow (specified-flux) boundaries. In this case, the flux through these boundaries is assumed to be zero because flow is generally parallel to these boundaries. The base or lower boundary of the model is also assumed to be no-flow, and is typically defined by the upper surface of the lower confining Pierre shale. On the basis of aquifer thickness and BTEX data (Sections 3 and 4), the saturated thickness of the aquifer was assumed to vary from 1 to 6 for the full saturated thickness to the confining layer. However, considering the significant variability of saturated thickness over the site, saturated thickness was estimated as a constant 3 feet in the model. Flow hydraulics were matched in the model by varying transmissivities (and therefore hydraulic conductivity) in the model without manipulating the saturated thickness array in the model. The upper model boundary is defined by the simulated water table surface.

Groundwater Elevation and Gradient

The water table elevation map presented in Figure 3.6 was used to define the starting heads input into the Bioplume II model. Groundwater flow in the vicinity of Area D is to the northeast at a maximum estimated gradient in the modeled area of approximately 0.017 ft/ft. Gradients appear greater near the source area and decrease northeast the site.

Limited data exist to document if seasonal precipitation rates significantly vary groundwater flow direction. Considering the deposits of lean clay and silt overlying the aquifer, it was assumed that minimal precipitation reaches the water table and that the observed water levels were representative of steady-state conditions. This assumption is further supported by the SESOIL model calculations summarized in Section 6. As described in later sections, the model was calibrated to the observed water table.

BTEX Concentrations

The total BTEX concentrations obtained from laboratory analytical results for each well location were used for model development. BTEX data collected during the 1991/1992 sampling events and the 1994 sampling event were used to calibrate the model. Appendix A presents dissolved BTEX data from the 1994 sampling event. Figure 4.2 presents the probable extent of benzene and total BTEX in groundwater based on these 1994 data. As described in Section 6, this model was calibrated using existing contaminant data and current site conditions to predict how dissolved contaminants would migrate in the future.

Contaminant Decay Coefficient

The discussion presented in Section 6 suggests that oxygen, manganese, sulfate and ferric iron are being used as electron acceptors during fuel hydrocarbon biodegradation at Area D. The modeling strategy pursued at this site involved using a site-specific BTEX decay coefficient that accounted for both aerobic and anaerobic processes.

The site-specific decay coefficient was calculated using a simple regression technique developed by Buscheck and Alcantar (1995). The decay coefficient is determined by coupling the regression of concentration versus distance for a dissolved plume assumed to be under steady-state conditions. This technique provides an analytical method to use site data to distinguish contaminant mass losses due to nondestructive chemical attenuation processes from contaminant mass losses due to destructive attenuation processes. Figure 2 illustrates how site-specific are used to derive the decay coefficient for individual BTEX compounds and total BTEX at Area D. The derivation of the site-specific decay coefficient using the results of this regression is summarized in Section 6.3.4 and Table 6.2. The decay coefficient determined for total BTEX at Area D is 0.00115 day^{-1}, which compares favorably to the saturated soil and groundwater degradation rates for these compounds found in the technical literature.

This regression technique defines a site-specific decay coefficient that accounts for the limiting effects of mixing, mass transfer, and kinetics that are operating at Area D. This is an important conservative assumption in the Bioplume II model. When using a DO-activated biodegradation rate, the model assumes that the total mass of DO is available to participate in BTEX degradation in accordance with mass stoichiometric relationships. As described in Section 6, only a fraction of the assimilative capacity of the saturated media, as calculated by mass stoichiometric relationships, is apparently used to biodegrade fuel hydrocarbons. Thus, if the model relied on electron mass, the effects of chemical destructive attenuation processes on chemical mass, concentration, and mobility over time may be overestimated. In contrast, use of the site-specific decay coefficient ensures that biodegradation effects as calculated from field scale evidence are incorporated into the model. Additionally, the fastest contaminant velocities that could be observed at this site were used to derive the site-specific decay coefficient. This also is an important assumption, because decay will become less effective in reducing contaminant mass as a function of distance as contaminant velocities increase. This means that the site-specific decay coefficients are conservative.

Model Calibration

Model calibration is an important component in the development of any numerical groundwater model. Calibration of the flow model demonstrates that the model is capable of matching hydraulic conditions observed at the site; calibration of a contaminant transport model superimposed upon the calibrated flow model helps verify that contaminant loading and transport conditions are being appropriately simulated. The numerical flow model developed for Area D was calibrated by altering transmissivity in a trial-and-error fashion until simulated heads approximated observed field values within a prescribed accuracy. After calibration of the flow model, the numerical transport model was calibrated by altering transport parameters in a trial-and-error fashion until the simulated BTEX plume approximated observed field values. Table 1 lists input parameters used for the modeling effort.

Water Table Calibration

The shallow water table at Area D was assumed to only be influenced by continuous recharge and discharge at the constant-head cells established at the upgradient and downgradient model boundaries. No surface water bodies exist in the immediate area that may affect the flow direction of the groundwater. The initial water levels at the constant-head cells were varied to calibrate the water table surface. Transmissivities were also varied in the model because of both the heterogeneity of sands, gravels, silts, and clays at the site. The transmissivities were varied in accordance to the range of hydraulic conductivity estimates derived from slug test data. Recharge from annual precipitation was omitted as a conservative model estimate because of low predicted recharge rates (see SESOIL model results). The model was calibrated under steady-state conditions.

Hydraulic conductivity is an important aquifer characteristic that determines the ability of the water-bearing strata to transmit groundwater. Transmissivity is the product of the hydraulic conductivity and the thickness of the aquifer. An accurate estimate of hydraulic conductivity is important to help quantify advective groundwater flow velocities and to define the flushing potential of the aquifer. According to the work of Rifai et al. (1988), the Bioplume II model is particularly sensitive to variations in hydraulic conductivity. Lower values of hydraulic conductivity result in slower-moving contaminants. These slower-moving contaminants will be simulated to degrade more rapidly than faster moving contaminants by using a constant decay coefficient. As discussed earlier, chemical decay will becomes more effective in reducing contaminant mass as a function of distance as contaminant velocities decrease. Higher values of hydraulic conductivity result in a faster-moving plume, which will not decay as effectively over distance as a slower-moving plume. The Bioplume II model for this site was calibrated using the highest hydraulic conductivities observed at the site. This is a critical conservative assumption in the Bioplume II model, which will serve to overestimate the extent of contaminant migration and underestimate the type of contaminant mass destruction over time at the site.

Estimated saturated thickness data were used in conjunction with estimates of the hydraulic conductivity to create an initial transmissivity grid for the entire model. Figure 3 shows the calibrated water table. Calibrated model hydraulic conductivities ranged from 1.61×10^{-5} foot per second (ft/sec) to 2.17×10^{-6} ft/sec (9.66×10^{-4} ft/min to 1.30×10^{-4} ft/min), which are estimated values of hydraulic conductivity for the site based on slug test data (Section 3).

Water level elevation data from 25 monitoring well locations were used to compare measured and simulated heads for flow calibration. The 25 selected monitoring well locations were: MW-1, MW-2, MW-5, MW-13, MW-14, MW-15, MW-16, MW-17, MW-18, MW-19, MW-20, MW-21, MW-23, MW-24, MW-25, MW-26, MW-27, MW-28, MW-29, MW-30, MW-31, MW-33, MW-34, MW-35, and MW-40.

The root mean square (RMS) error is commonly used to express the average difference between simulated and measured heads. RMS error is the average of the squared differences between measured and simulated heads, and can be expressed as:

$$\text{RMS} = \left[\frac{1}{n} \sum_{i=1}^{n} (h_m - h_s)_i^2 \right]^{0.5}$$

Where: n = the number of points where heads are being compared

h_m = measured head value

h_s = simulated head value.

The RMS error between observed and calibrated values at the 12 comparison points was 0.50 foot, which corresponds to a calibration error of 7.8 percent (water levels dropped approximately 6.36 feet over the length of the model grid). RMS error calculations are summarized at the end of this appendix. A plot of measured versus calibrated heads shows a random distribution of points around a straight line, as shown at the end of this appendix. Deviation of points from a straight line should be randomly distributed in such a plot of results from computer simulations (Anderson and Woessner, 1992).

In solving the groundwater flow equation, Bioplume II establishes the water table surface and calculates an overall hydraulic balance that accounts for the numerical difference between flux into and out of the system. The hydraulic mass balance for the calibrated model was excellent, with 99.9 percent of the water flux into and out of the system being numerically accounted for (i.e., a 0.1-percent error). According to Anderson and Woessner (1992), a mass balance error of around 1 percent is acceptable.

BTEX Plume Calibration

Model input parameters affecting the distribution and concentration of the simulated BTEX plume were not modified to match model predictions with dissolved total BTEX concentrations collected from either FMG data (1991 and 1992) or Parson ES data (1994) Physical, chemical, and biological parameters estimated for the site, with the exception of transmissivity, were set to produce a calibrated model. Although the 1991/1992 data were not used to calibrate the model to sequential time events, the 1991/1992 simulated plume is in good agreement with the dissolved plume developed from the FMG data sets. Figure 6.4 compares the observed total BTEX plume in 1994 to the simulated 1994 total BTEX plume. The general geometry of the simulated plume closely resembles that of the observed plume. However, the actual mass of contaminants in the groundwater in 1994 as simulated by the Bioplume II model is less than the mass observed during the 1994 field effort. Close agreement between maximum measured total BTEX concentrations was achieved.

Because pockets of LNAPL could still act as a significant contaminant source at the site (i.e., variable levels of LNAPL have been encountered at the site during previous investigations), Parsons ES opted to include model injection wells to simulate partitioning of BTEX compounds from the JP-4 source into the groundwater. Available soil data suggest that residual contamination is insignificant at the site because of low predicted infiltration rates (see SESOIL model results). The transport pathway of contaminants from JP-4 to groundwater is through transfer at the groundwater/JP-4 interface. The locations of the injection wells are shown on Figure 4. Three injection wells were placed in the estimated LNAPL source area to produce a BTEX plume representative of 1994 site conditions. Although LNAPL contamination has only been encountered in MW-6 and possibly MW-4, it became apparent that a significant source of contamination may also exist upgradient (southwest) of MW-6 to account for the shape of the groundwater plume at the source area. Hence, three injection wells were placed in model grid cells (10,5), (11,6), and (12,7), which provides a possible source area that extends from MW-40 to MW-6.

While the term "injection well" suggests contaminants are being introduced at a point, Bioplume II assumes that contamination introduced at a well instantly equilibrates throughout the entire cell in which the well is located. The injection rate for the cells was set at 1.0 x 10^{-8} cubic foot per second (ft^3/sec), a value low enough that the flow calibration in the source area was not affected. After converting the predicted dissolution rate of BTEX contamination from LNAPL at the site (discussed in the following paragraphs), relatively high BTEX concentrations were needed in injection wells because of the low volumetric injection rates.

BTEX concentrations used in injection wells to simulate existing plume conditions were obtained from the free-product partitioning effect calculations discussed in Section 6.6.1. LNAPL is predicted to reside in pools in the source area and separated by erratic bedrock stratigraphy and/or pockets of silty or clayey sands. Two 10-feet outer-diameter (OD) LNAPL pools were predicted to exist in the source area at the site as simplified conceptualizations of source conditions. BTEX dissolution rates from these conceptualized LNAPL pools were averaged over the three model cells used to simulate the dissolution of BTEX into groundwater at the site. Hence, the modeled source area of three cells is approximately 0.14 acres. Continuing dissolution of BTEX compounds into water, coupled with potential volatilization losses, were predicted to slowly reduce, or weather, BTEX mass from the LNAPL pools. Therefore, the rate of BTEX dissolution into groundwater in the model was continuously reduced in the model to simulate weathering. Estimated weathering rates were determined by the rate at which BTEX could dissolve into groundwater, which in turn was dependent on concentration gradients between the LNAPL pool and the groundwater. Diminishing BTEX mass (as a result of weathering) in the LNAPL pool cause smaller concentration gradients at the groundwater/LNAPL interface, which in turn decreased the weathering of the LNAPL. As a result, weathering rates (mostly caused by BTEX dissolution into groundwater) and dissolution rates decrease at the site and in the model over time. Complete loss of BTEX mass and the elimination of a source term in the model occurred after 11 years.

The objective of the contaminant calibration step was to obtain a modeled plume that equaled or exceeded the existing plume in terms of downgradient extent and that could be extrapolated back to compare to historical data. The simulated 1994 plume closely resembles the observed plume in 1994 (Figure 6.4). The model predicts that after the first few years of migration, the groundwater plume is expected to travel significantly farther downgradient than currently observed. The plume reaches its maximum extent after approximately 20 years where the maximum concentration in the plume is in the source area (since weathered) at approximately 85 μg/L. The BTEX plume is expected to concentrations of 5 μg/L within 30 years (year 2025), after which the plume is completely destroyed through natural chemical destructive attenuation processes.

Overall, the calibrated model conservatively represents how dissolved BTEX contamination is behaving in groundwater at Area D. The conservativeness in the model is strongly represented by migration rates and patterns after the first few years (>five years) that are not currently evident at the site, especially considering that contamination at the site is suspected to have first occurred a minimum of five years ago (leak tests on the fuel system failed in late 1990). The Bioplume II model is used to estimate the maximum extent of contaminant migration expected at the site over time. Thus, the model simulations were used to estimate how far measurable concentrations of total BTEX are expected to travel through the preferential contaminant channels thought to be present at the site.

Discussion of Important Plume Calibration Parameters

Few transport parameters were varied during plume calibration because of the sufficient amount of available site-specific data. Hence, it was not necessary to vary the modeling parameters of dispersivity, retardation, and contaminant decay to achieve a model calibration. Only transmissivity values in the model domain and range were varied to achieve the model calibration. However, the impact on the size and shape of the simulated plume and the estimation method used for the model parameters dispersivity, retardation, and contaminant decay rate is discussed below.

Dispersivity

Much controversy surrounds the concepts of dispersion and dispersivity. Longitudinal dispersivity values for sediments similar to those found at the site range from 0.1 to 200 feet (Walton, 1988). Longitudinal dispersivity was estimated as 9.2 feet, using one-tenth (0.1) of the distance between the estimated spill source of the 1992 BTEX plume and the longitudinal centroid of the 1992 BTEX plume. Dispersivity estimation calculations are included at the end of this appendix. Transverse dispersivity values generally are estimated as one-tenth (0.1) of the longitudinal dispersivity values (Domenico and Schwartz, 1990).

During plume calibration, longitudinal dispersivity was maintained at 9.2 feet. This value was low compared to possible values that could have been used, but was justified by an estimate of dispersivity included at the end of this appendix. The use of a moderate dispersivity value of 9.2 feet was a good estimate for sandy and gravelly stratigraphy predominant at the site. Similarly, the ratio of transverse dispersivity to longitudinal dispersivity was maintained at 0.1 to help reproduce the plume width observed at the site.

Coefficient of Retardation

Retardation of the BTEX compounds relative to the advective velocity of the groundwater occurs when BTEX molecules are sorbed to the aquifer matrix. The coefficients of retardation for the BTEX compounds were calculated based on measured total organic carbon (TOC) concentrations in the soils in and near the saturated zone at the site (Section 3), an assumed bulk density of 1.6 grams/cubic centimeter (Freeze and Cherry, 1979), and published values of the soil sorption coefficient (K_{oc}) for the BTEX compounds, as listed by Wiedemeier *et al.* (1995). The results of these calculations are summarized in Table 2. A final value of 2.77 for the retardation coefficient was used for the BTEX compounds. This value is relatively high, but is consistent with TOC values taken at the site which suggest that a great deal of organic matter exists in the soils. As with dispersivity and the reaeration coefficient, this variable was not adjusted in the model calibration.

Contaminant Decay Coefficient

The contaminant decay coefficient is a first-order rate constant that can be used in Bioplume II to simulate aerobic and anaerobic contaminant removal. The contaminant decay coefficient (or biodegradation coefficient) is estimated with an analytical solution of the general one-dimensional transport equation modified by Buscheck and Alcantar (1995). A contaminant decay coefficient of 0.0012 day^{-1} is derived by the above method. As with dispersivity and retardation, this site-specific value was not varied in the model calibration process.

Sensitivity Analysis

The purpose of the sensitivity analyses is to determine the effect of varying model input parameters on model output. Based on the work of Rifai *et al.* (1988), the Bioplume II model is most sensitive to changes in the contaminant decay coefficient and the hydraulic conductivity of the media, and is less sensitive to changes in the retardation factor, porosity, and dispersivity. The effect of aerobic and anaerobic processes on BTEX mass are included together in the overall contaminant decay coefficient. Because the porosity was not varied and the dispersivity was not significantly changed, the sensitivity analysis was conducted by varying the transmissivity, the contaminant decay coefficient, and the coefficient of retardation.

To perform the sensitivity analyses, the calibrated model was adjusted by systematically changing the aforementioned parameters individually, and then comparing the new model runs to the original calibrated model. The sensitivity models were run for a 10-year period so that the independent effect of each variable could be assessed at predicted 2005 concentrations. As a result, six sensitivity runs of the calibrated model were made, with the following variations:

1) Transmissivity uniformly increased by a factor of 5;

2) Transmissivity uniformly decreased by a factor of 5;

3) Coefficient of contaminant decay increased by 10;

4) Coefficient of contaminant decay decreased by 10;

5) Coefficient of retardation increased by 25 percent; and,

6) Coefficient of retardation decreased by 25 percent;

The results of the sensitivity analyses are shown graphically in Figures 5, 6, and 7. These figures show the results of the model simulations in total BTEX concentrations versus distance along the centerline of the plume (11th model grid column). This manner of displaying data is useful because BTEX concentrations are highest in the 11th column, and the plume extends the farthest downgradient from the source of contamination. These figures allow easy visualization of the changes in BTEX concentration caused by varying model input parameters.

The effects of varying transmissivity are shown by Figure 5. Uniformly increasing the transmissivity by a factor of 5 altered the plume shape such that the maximum observed concentrations in the source cell area were 4,200 µg/L, compared to the calibrated maximum of 2,000 µg/L. In this case, the BTEX plume extended farther downgradient and off the model grid. Lower BTEX concentrations in the center of the plume are a result of an increased advective velocity that reduced the residence time of groundwater below the source area. Thus, less BTEX contamination was able to dissolve into the groundwater from LNAPL. Increased groundwater velocity also caused BTEX contamination to migrate farther downgradient before being effectively biodegraded.

In contrast, decreasing the transmissivity by a factor of 5 slowed overall plume migration, which shortened the plume by approximately 225 feet. This, in turn, caused an increase in maximum BTEX levels. Increased BTEX concentrations in the plume area are caused by a reduction in the plume travel rate, thereby allowing greater BTEX concentrations to dissolve into groundwater in the source area before being biodegraded downgradient.

The effects of varying the contaminant decay coefficient are illustrated by Figure 6. Increasing this parameter by 10 results in a dramatic reduction of the maximum BTEX concentrations by 1,700 µg/L. In addition, the front of the plume recedes approximately

450 feet. This is a result of increased biodegradation. Conversely, decreasing this coefficient by 10 decreases biodegradation and increases the maximum length of the plume by at least 100 feet (plume migrates beyond model grid). The corresponding increase in the computed maximum BTEX concentrations in the plume center was 2,300 µg/L.

The effects of varying the coefficient of retardation (R) are shown on Figure 7. Increasing R by 25 percent caused little effect with either the BTEX concentrations in the source area or with the downgradient extent. The BTEX mass in the source area increased as a result of increased retardation. Decreasing R by 15 percent slightly accelerated plume migration because less contaminants were sorbed to soil particles and created a faster moving BTEX plume.

The results of the sensitivity analyses suggest that the calibrated model parameters used for this Bioplume II model match observed conditions well (see Figure 6.4). The calibrated model is sensitive to all the parameters varied, and especially sensitive to transmissivity and the contaminant decay coefficient. Increasing transmissivities or the decay coefficient reduced the predicted BTEX concentrations and/or reduced the predicted plume length. Lowering transmissivity increased source concentrations and reduced plume length. Lowering the reaeration coefficient and the coefficient of retardation tended to lengthen the plume beyond calibrated conditions.

Simulating LNAPL Removal

The effect of source reduction through wicking, bioventing, and natural weathering was evaluated with the Bioplume II model (Alternative 2). Conceptually, wicking units are placed at the source of contamination to maximize both LNAPL removal. Passive wicking and bioventing was simulated in the Bioplume II model by reducing LNAPL pool volumes and the source strength of BTEX over time. Hence, the radius of the individual LNAPL plumes were estimated to be reduced at a rate of 25 percent per year for the first 2 years of operation. The wicking system was assumed to have removed all recoverable LNAPL from the source area at the end of two years. After the initialreductions, the LNAPL source was assumed to continue weathering over time. BTEX concentrations in the LNAPL pools were assumed to be completely weathered after 11 years.

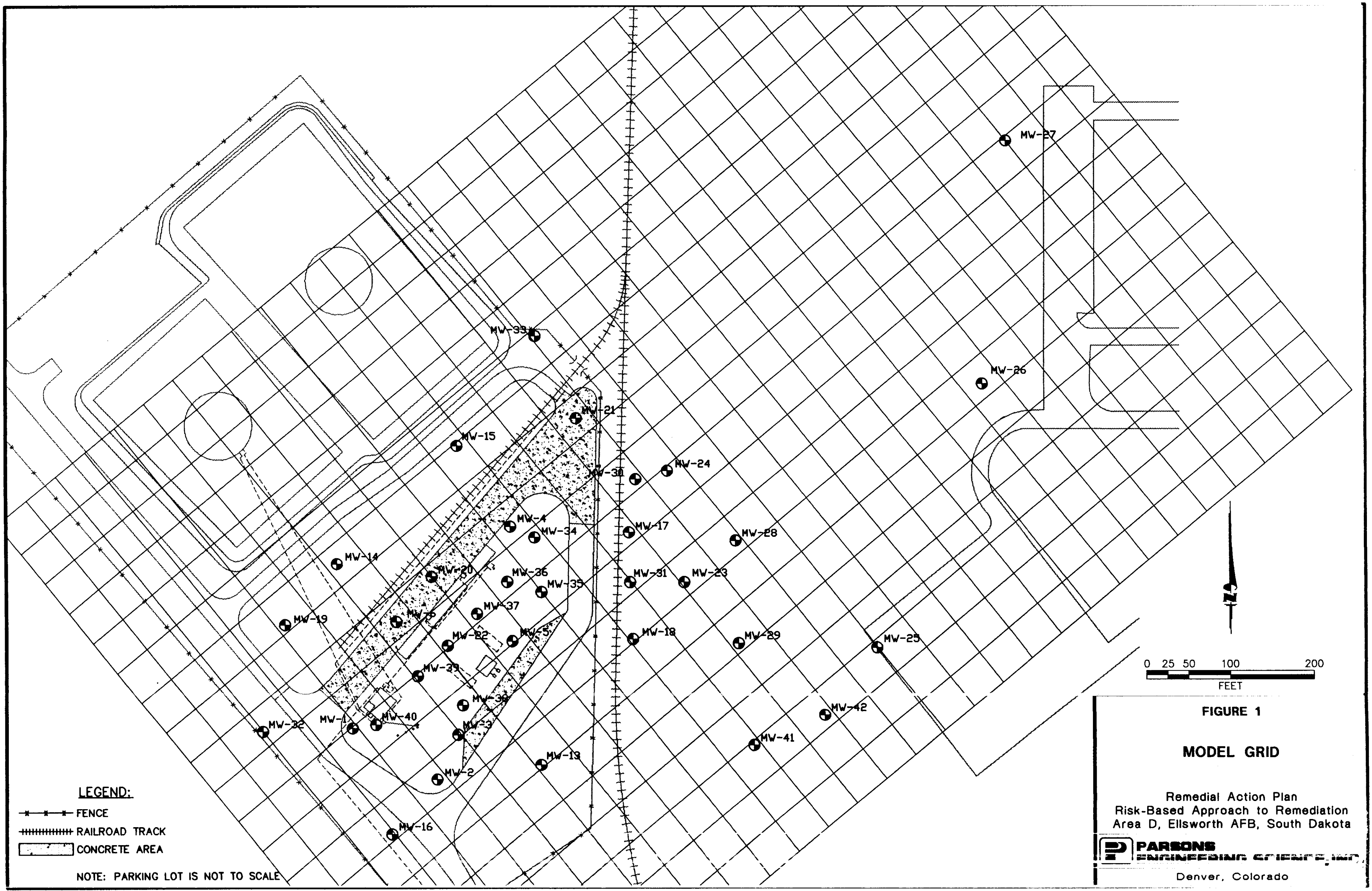

FIGURE 1

MODEL GRID

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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FIGURE 2 (DATA INPUT)
DATA USED IN BUSCHECK AND ALCANTAR SPATIAL REGRESSION FOR A BIODEGRADATION RATE
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Sampling Location	Travel Time (days)	Distance Downgradient (ft)	Measured Benzene (ug/L)	Measured Toluene (ug/L)	Measured Ethylbenzene (ug/L)	Measured Total Xylenes (ug/L)	Measured BTEX (ug/L)	Measured Naphthalene (ug/L)
MW-6	0	0	2000	35	640	2700	5375	300
MW-31	215.3846154	280	1500	8.3	470	1700	3678.3	180
MW-29	307.6923077	400	260	1.2	87	240	588.2	28

Figure 2
Spatial Regression Analysis for Biodegradation Rates in Saturated Media
Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

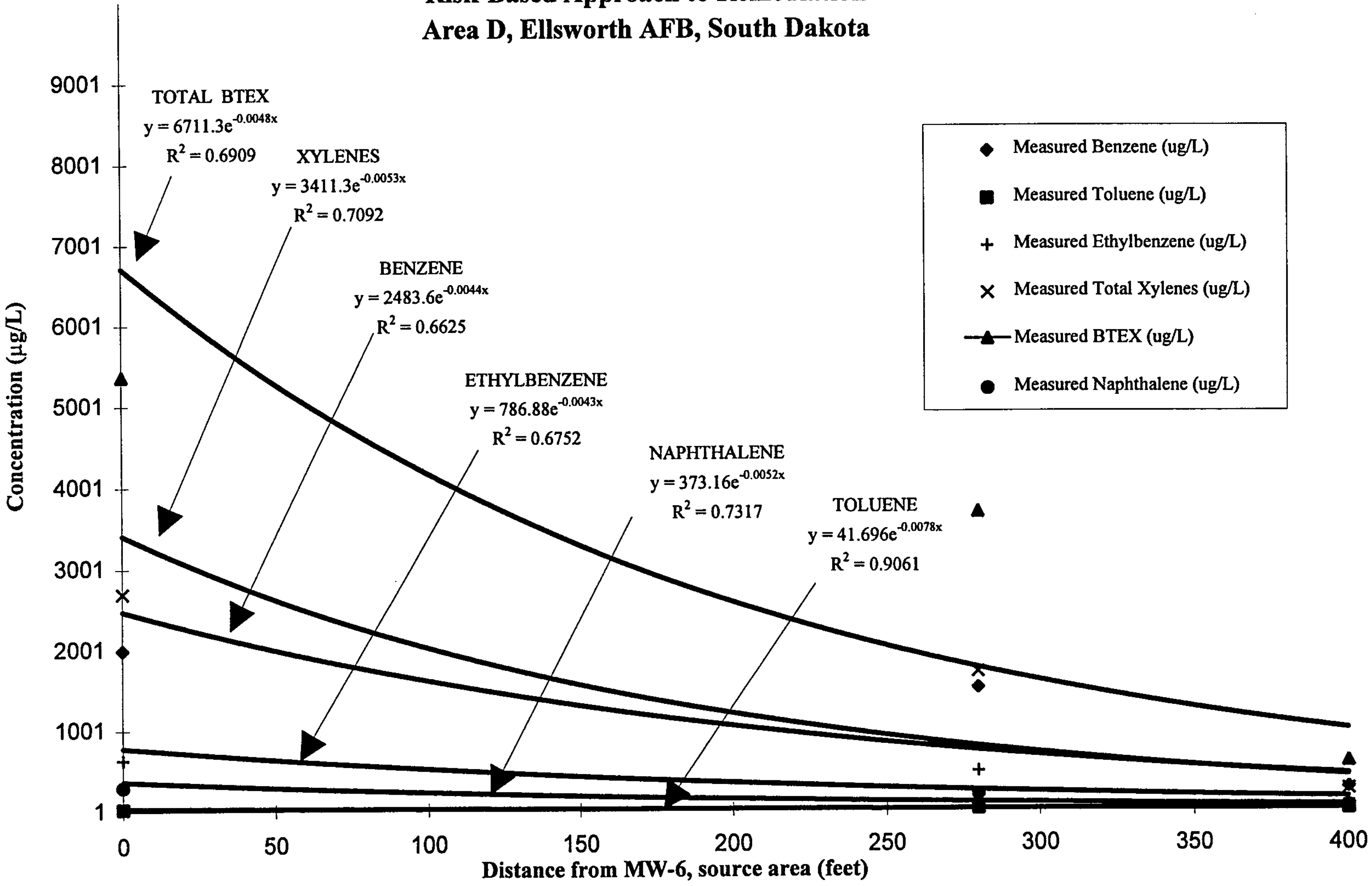


TABLE 1
BIOPLUME II MODEL INPUT PARAMETERS
AREA D
ELLSWORTH AIR FORCE BASE
RAPID CITY, SOUTH DAKOTA

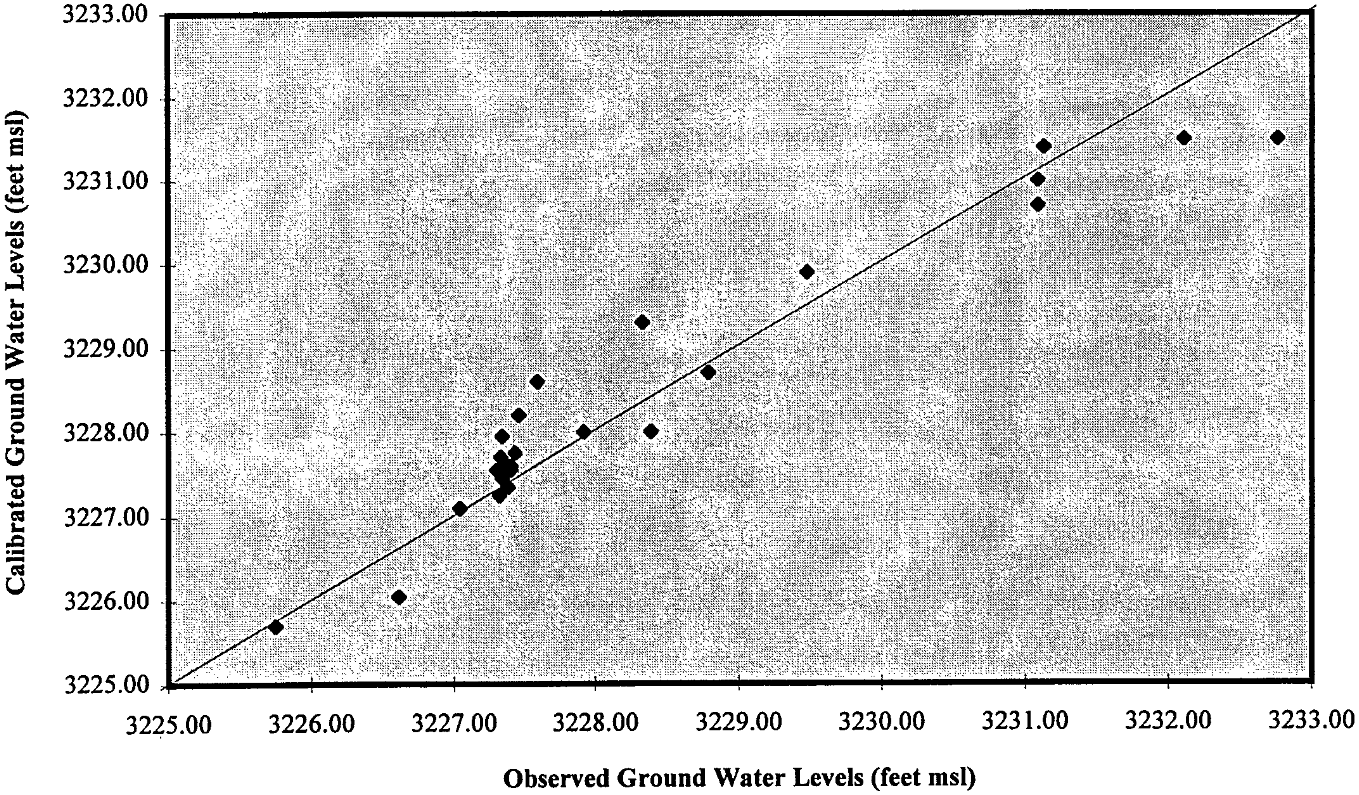
			Model Runs	
Parameter	Description	Calibrated Model Setup	AD1	AD2[c/]
NTIM	Maximum number of time steps in a pumping period	1	1	1
NPMP	Number of Pumping Periods	40	40	40
NX	Number of nodes in the X direction	20	20	20
NY	Number of nodes in the Y direction	30	30	30
NPMAX	Maximum number of Particles NPMAX=(NX-2)(NY-2)(NPTPND) + (Ns[a/])(NPTPND) + 250	5137	5137	5137
NPNT	Time step interval for printing data	1	1	1
NITP	Number of iteration parameters	7	7	7
NUMOBS	Number of observation points	0	1	1
ITMAX	Maximum allowable number of iterations in ADIP [b/]	200	200	200
NREC	Number of pumping or injection wells	13	5	5
NPTPND	Initial number of particles per node	9	9	9
NCODES	Number of node identification codes	1	1	1
NPNTMV	Particle movement interval (IMOV)	0	0	0
NPNTVL	Option for printing computed velocities	1	1	1
NPNTD	Option to print computed dispersion equation coefficients	0	1	1
NPDELC	Option to print computed changes in concentration	0	1	1
NPNCHV	Option to punch velocity data	0	0	0
NREACT	Option for biodegradation, retardation and decay	1	1	1
PINT	Pumping period (years)	40	40	40
TOL	Convergence criteria in ADIP	0.001	0.001	0.001
POROS	Effective porosity	0.30	0.30	0.30
BETA	Characteristic length (long. dispersivity; feet)	9.2	9.2	9.2
S	Storage Coefficient	0 (Steady-State)	0	0
TIMX	Time increment multiplier for transient flow	-	-	-
TINIT	Size of initial time step (seconds)	-	-	-
XDEL	Width of finite difference cell in the x direction (feet)	45	45	45
YDEL	Width of finite difference cell in the y direction (feet)	45	45	45
DLTRAT	Ratio of transverse to longitudinal dispersivity	0.1	0.1	0.1
CELDIS	Maximum cell distance per particle move	0.5	0.5	0.5
ANFCTR	Ratio of Tyy to Txx (1 = isotropic)	1	1	1
DK	Distribution coefficient	0.332	0.332	0.332
RHOB	Bulk density of the solid (grams/cubic centimeter)	1.6	1.6	1.6
THALF	Half-life of the solute	-	-	-
DEC1	Anaerobic decay coefficient (day^{-1})	-	-	-
DEC2	Reaeration coefficient (day^{-1})	0.0012	0.0012	0.0012
F	Stoichiometric Ratio of Hydrocarbons to Oxygen	3.14	3.14	3.14

[a/] Ns = Number of nodes that represent fluid sources (wells or constant head cells)

[b/] ADIP = Alternating-direction implicit procedure (subroutine for solving groundwater flow equation)

[c/] Identical to model KC1 with the exception that wicking units were added to simulate the reduction of LNAPL volumes.

Observed Heads Vs. Calibrated Heads
for the Calibrated Groundwater Model
Area D
Ellsworth AFB, South Dakota



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Mean Error, Mean Average Error, and Root-Mean-Square Error for the Calibrated Ground Water Model
Area D
Elleswurth AFB, South Dakota

Location	Actual Water Level (h_m)[a/]	Calibrated Water Level (h_s)[a/]	h_m-h_s	abs(h_m-h_s)	$(h_m-h_s)^2$
MW-1	3232.11	3231.50	-0.61	0.61	0.37
MW-2	3231.13	3231.40	0.27	0.27	0.07
MW-5	3227.59	3228.60	1.01	1.01	1.02
MW-13	3231.09	3230.70	-0.39	0.39	0.15
MW-14	3228.33	3229.30	0.97	0.97	0.94
MW-15	3227.34	3227.95	0.61	0.61	0.37
MW-16	3231.09	3231.00	-0.09	0.09	0.01
MW-17	3227.40	3227.60	0.20	0.20	0.04
MW-18	3227.92	3228.00	0.08	0.08	0.01
MW-19	3229.48	3229.90	0.42	0.42	0.18
MW-20	3228.79	3228.70	-0.09	0.09	0.01
MW-21	3227.30	3227.55	0.25	0.25	0.06
MW-23	3227.37	3227.60	0.23	0.23	0.05
MW-24	3227.38	3227.35	-0.03	0.03	0.00
MW-25	3227.04	3227.10	0.06	0.06	0.00
MW-26	3226.61	3226.05	-0.56	0.56	0.31
MW-27	3225.75	3225.70	-0.05	0.05	0.00
MW-28	3227.32	3227.25	-0.07	0.07	0.00
MW-29	3227.33	3227.70	0.37	0.37	0.14
MW-30	3227.40	3227.55	0.15	0.15	0.02
MW-31	3227.43	3227.75	0.32	0.32	0.10
MW-33	3227.34	3227.45	0.11	0.11	0.01
MW-34	3228.39	3228.00	-0.39	0.39	0.15
MW-35	3227.46	3228.20	0.74	0.74	0.55
MW-40	3232.76	3231.50	-1.26	1.26	1.59
Total:	71020.54	71023.7	2.25	9.33	6.17

ME[b/] = 0.09
MAE[c/] = 0.37
RMS[d/] = 0.50

[a/] Water levels are in feet mean-sea-level.

[b/] ME = Mean Error =1/n x (h_m-h_s).

[c/] MAE = Mean Average Error = 1/n x $|(h_m-h_s)|$.

[d/] RMS = Root-Mean-Square (RMS) Error = $(1/n \text{ x } (h_m-h_s)^2)^{0.5}$.

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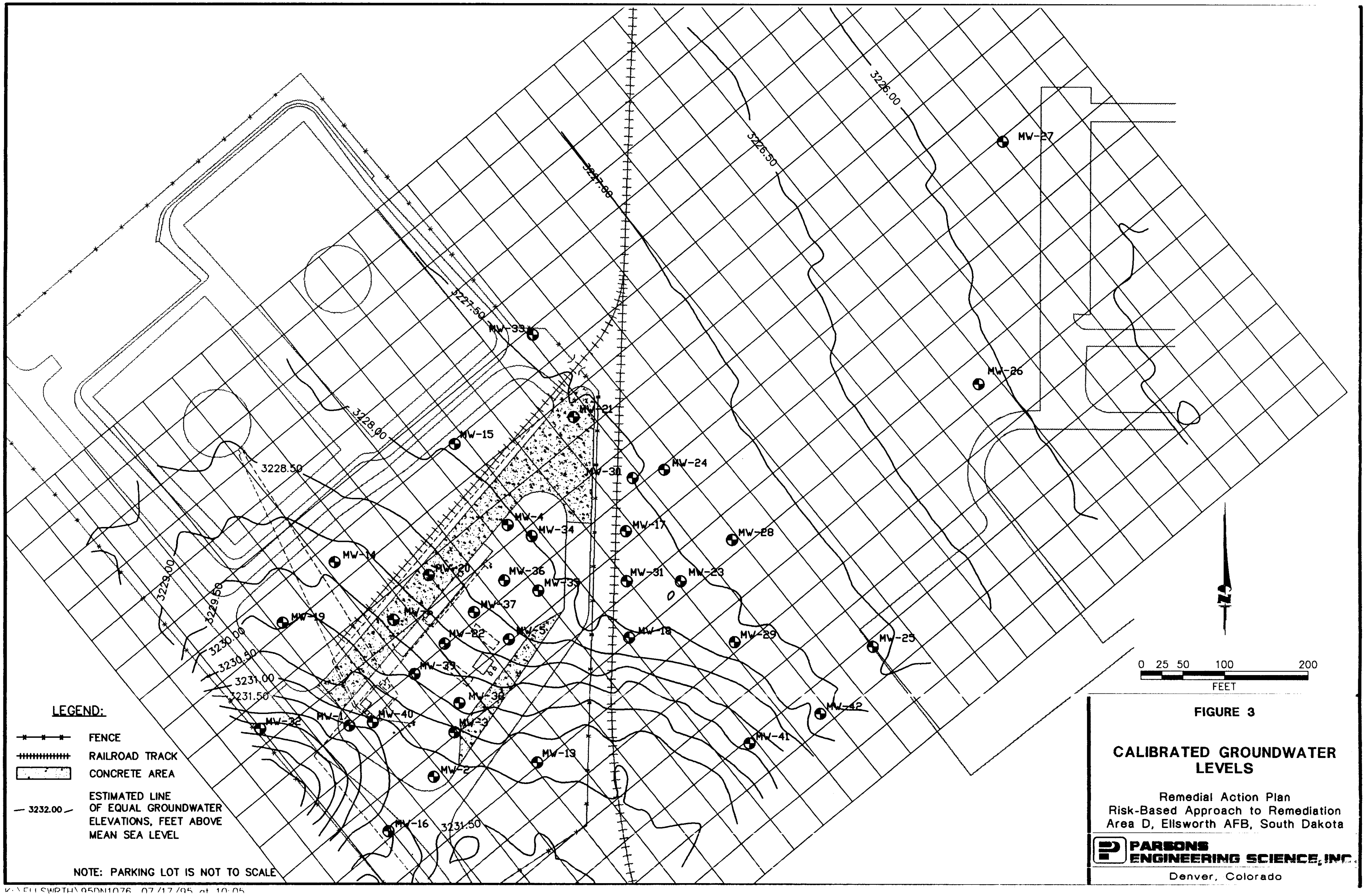

FIGURE 3

CALIBRATED GROUNDWATER LEVELS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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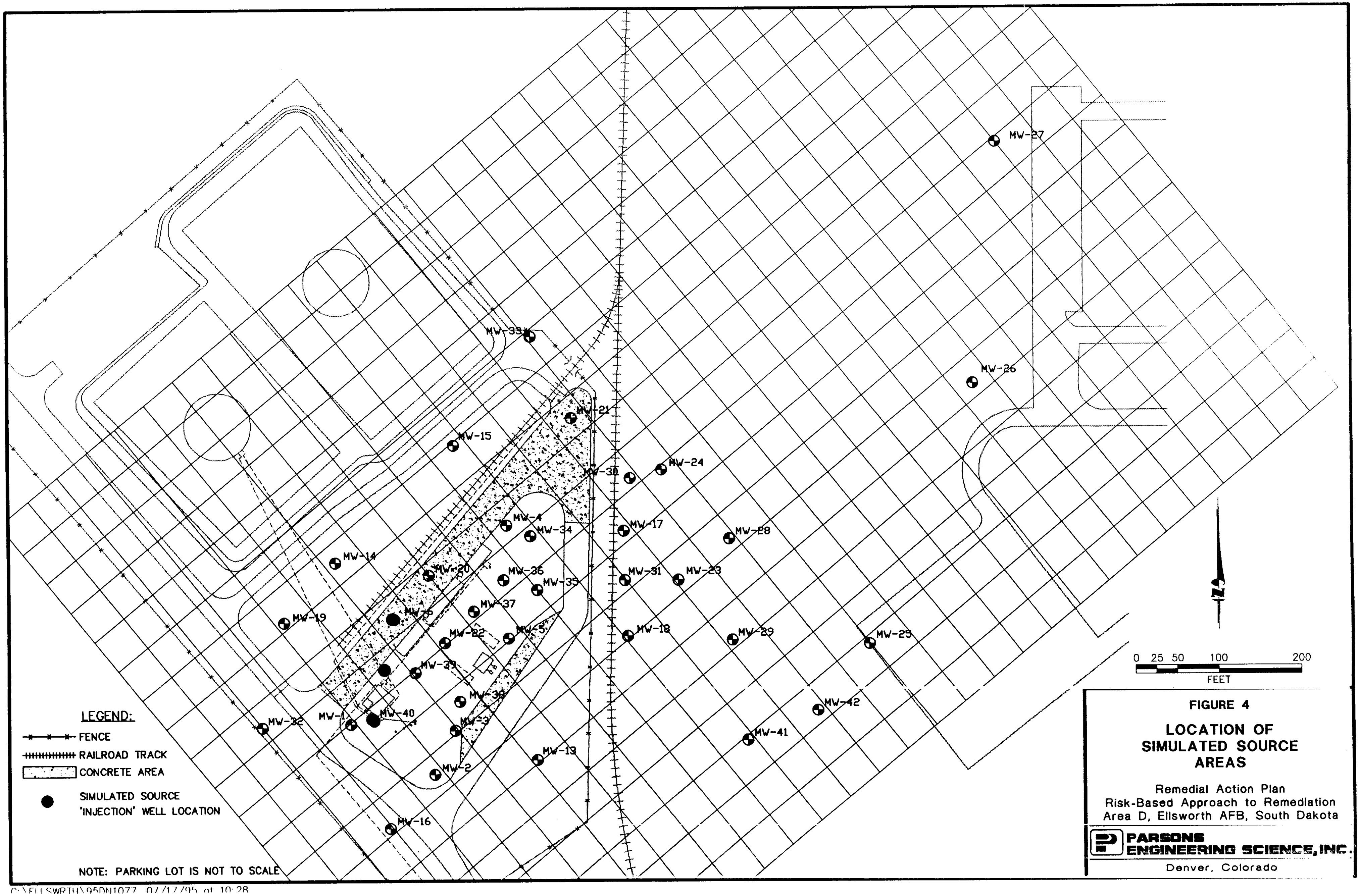

FIGURE 4

LOCATION OF SIMULATED SOURCE AREAS

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

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TABLE 2
CALCULATION OF RETARDATION COEFFICIENTS
RISK-BASED APPROACH TO REMEDIATION
AREA D
ELLSWORTH AFB, SOUTH DAKOTA

Compound	K_{oc} (L/kg [a])	Maximum Fraction Organic Carbon [b]	Minimum Fraction Organic Carbon [b]	Average Fraction Organic Carbon [b]	Distribution Coefficient K_d (L/kg)			Bulk Density (kg/L)[d]	Effective Porosity	Coefficient of Retardation		
					Maximum[c1]	Minimum[c2]	Average[c3]			Maximum	Minimum	Average
Benzene	79	0.011	0.0042	0.0076	0.869	0.332	0.600	1.60	0.30	5.63	2.77	4.20
Toluene	190	0.011	0.0042	0.0076	2.090	0.798	1.444	1.60	0.30	12.15	5.26	8.70
Ethylbenzene	468	0.011	0.0042	0.0076	5.148	1.966	3.557	1.60	0.30	28.46	11.48	19.97
m-xylene	405	0.011	0.0042	0.0076	4.455	1.701	3.078	1.60	0.30	24.76	10.07	17.42
o-xylene	422	0.011	0.0042	0.0076	4.642	1.772	3.207	1.60	0.30	25.76	10.45	18.11
p-xylene	357	0.011	0.0042	0.0076	3.927	1.499	2.713	1.60	0.30	21.94	9.00	15.47

NOTES:

[a] From technical protocol (Wiedemeier *et al.*, 1994).

[b] From Area D Site data.

[c1] K_d = Maximum Fraction Organic Carbon x K_{oc}.

[c2] K_d = Minimum Fraction Organic Carbon x K_{oc}.

[c3] K_d = Average Fraction Organic Carbon x K_{oc}.

[d] Literature values.

FIGURE 5
PLOT OF TOTAL BTEX VS. DISTANCE ALONG PLUME CENTERLINE WITH VARYING TRANSMISSIVITY
Area D
Ellsworth AFB, South Dakota

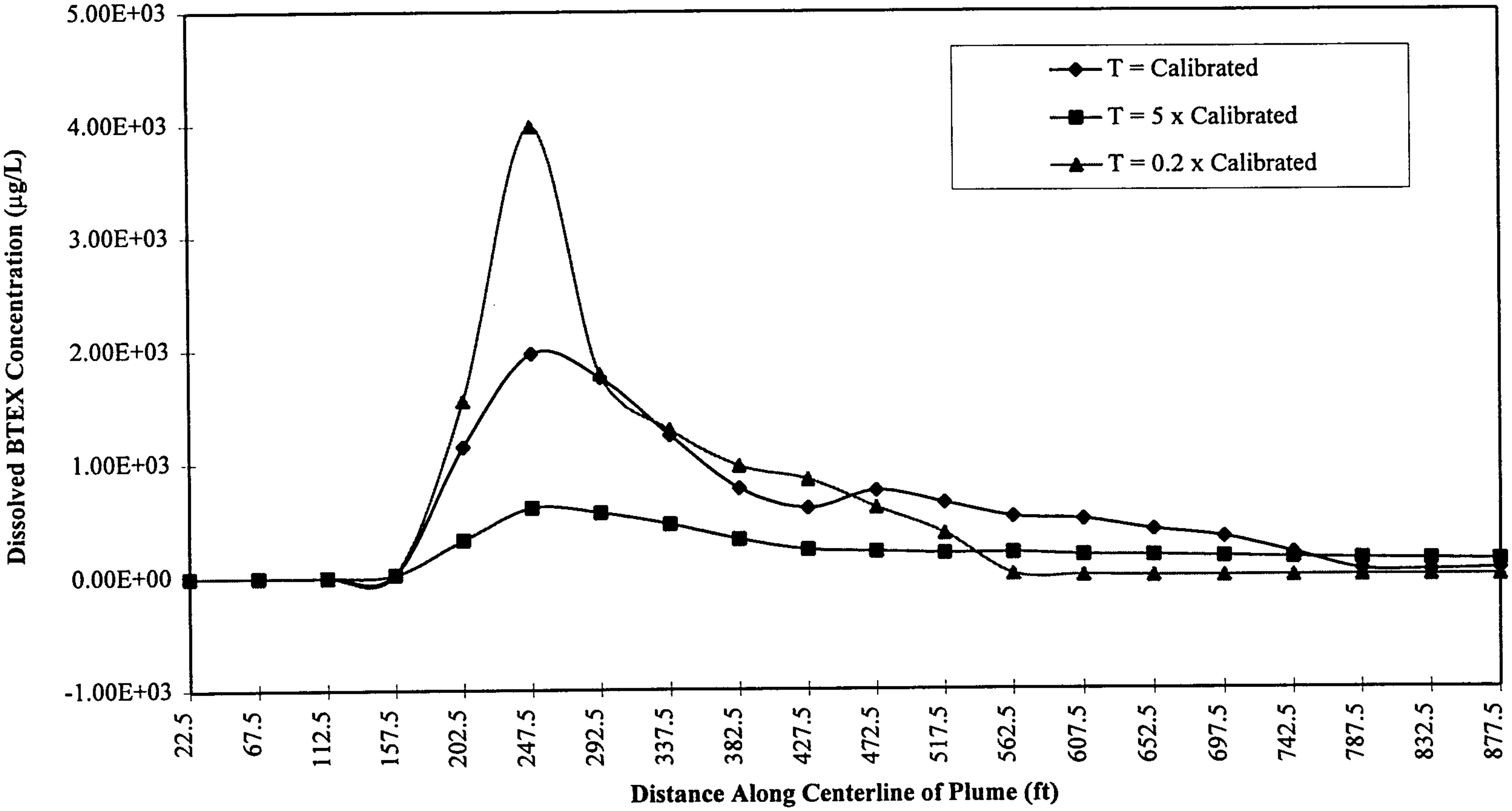

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FIGURE 6
PLOT OF TOTAL BTEX VS. DISTANCE ALONG PLUME CENTERLINE WITH VARYING DECAY COEFFICIENT
Area D
Ellsworth AFB, South Dakota

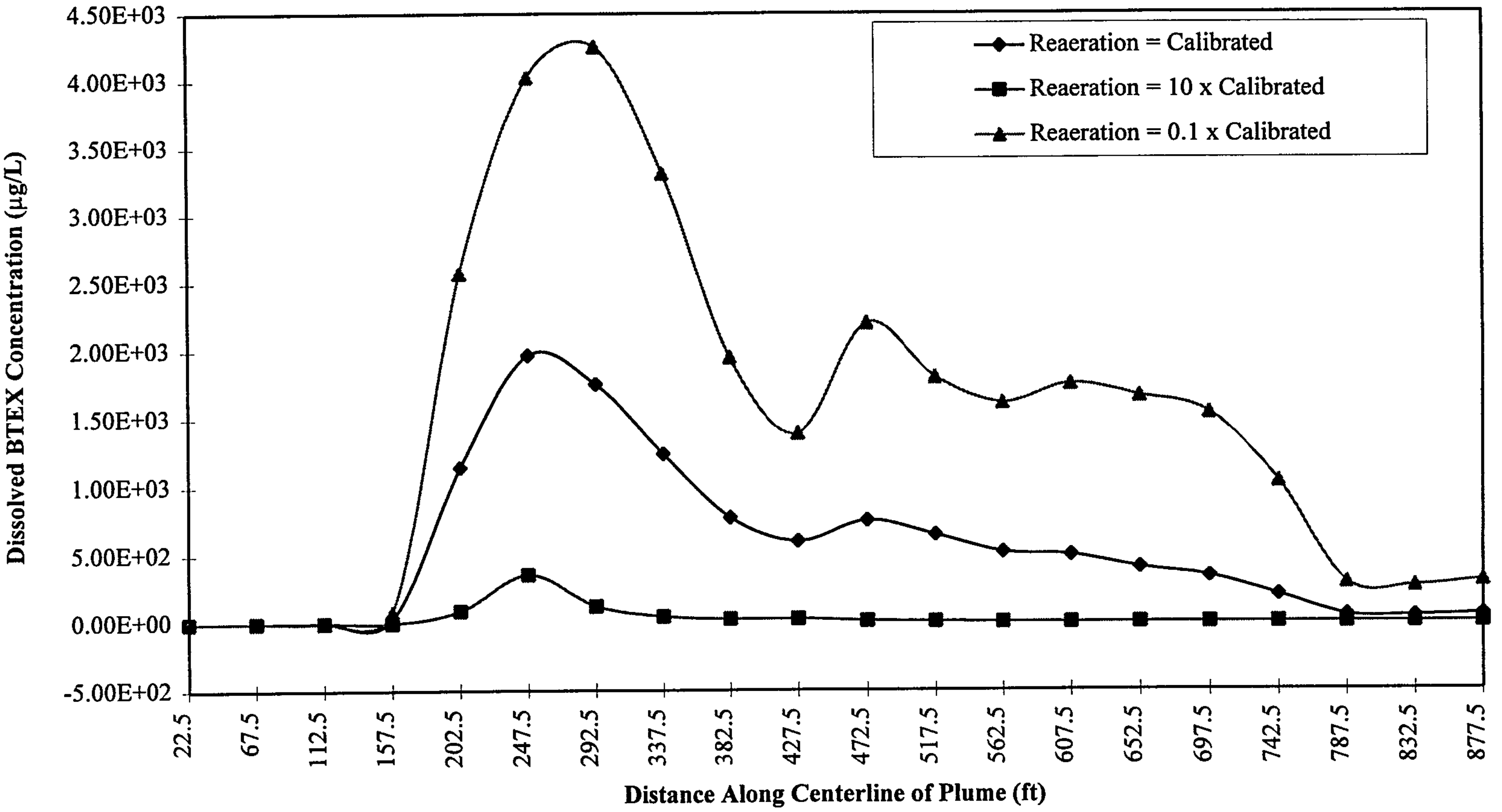

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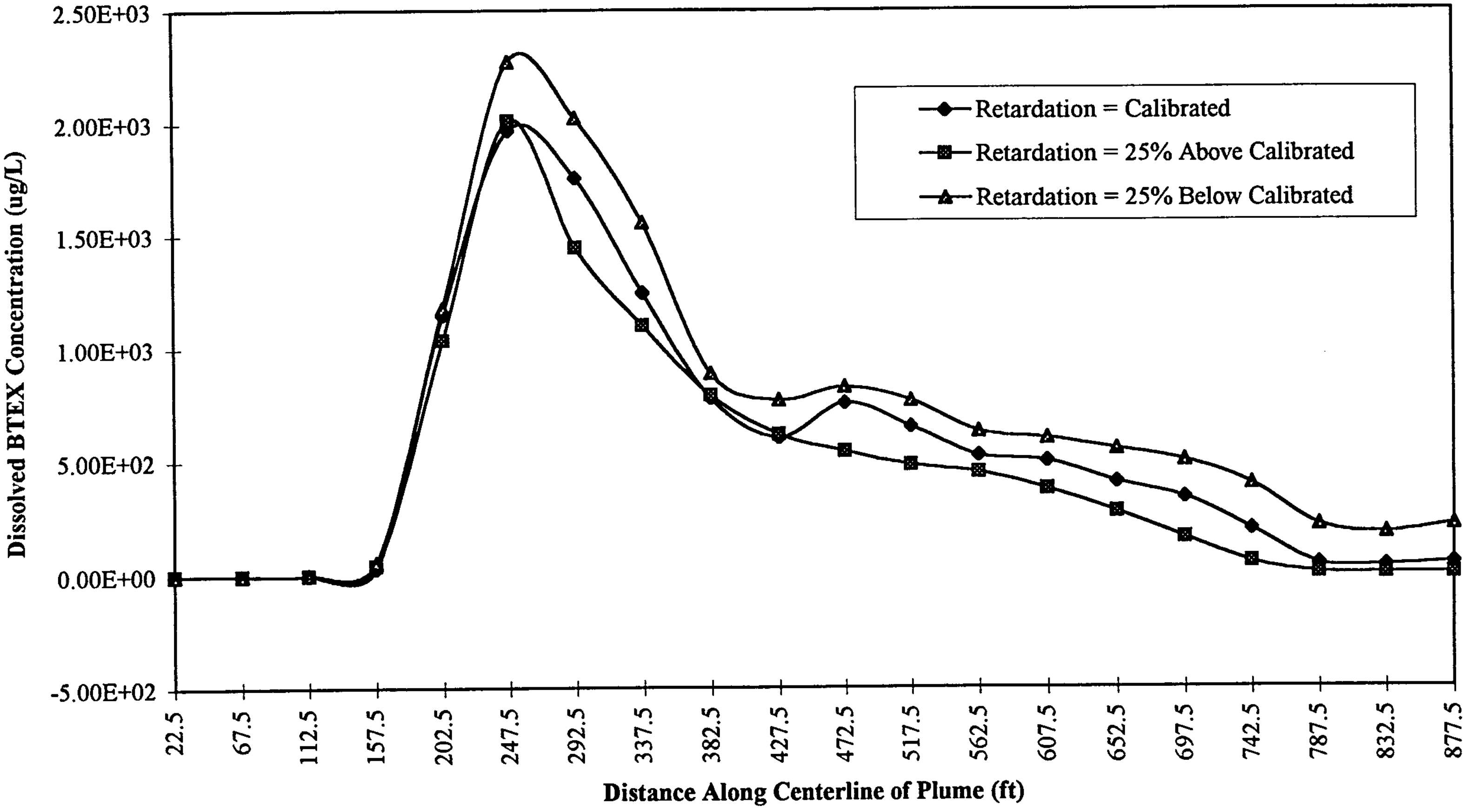
FIGURE 7
PLOT OF TOTAL BTEX VS. DISTANCE ALONG PLUME CENTERLINE WITH VARYING RETARDATION
Area D
Ellsworth AFB, South Dakota



		longitudinal mass
distance (ft)	**concnetraitons**	**distance*concentration**
-65	2250	-146250
	3000	-195000
	900	-58500
65	1700	110500
	4500	292500
	1500	97500
195	500	97500
	3900	760500
	700	136500
325	500	162500
	2000	650000
	300	97500
total=	21750	2005250
	longitudinal mass/mass	92.1954023
		divide by 10
	dispersivity =	9.2

APPENDIX F

SOURCE REDUCTION TESTING RESULTS

Respiration Test
Area D
Ellsworth AFB, SD

Monitoring Point	Date	Days Elapsed (frac. days)	Time	Hrs elapsed (fractional days)	Days Elapsed	Elapsed Time (min. x 1000)	O2%	CO2%	Total Hydro-carbon	Helium	Comments	Trend of O2/ Time	New x-values	k
VW-1	08/27/93	0.00	09:03	0.00	0.00	0.00	19.2	0.3	830	1.6		18.9283373	0	0.01669
VW-1	08/27/93	0.00	10:09	0.05	0.05	0.07	17.9	0.2	1200	1.3		10.247874	0.52	
VW-1	08/27/93	0.00	11:02	0.08	0.08	0.12	16.8	0.2	1800	1.1				
VW-1	08/27/93	0.00	13:03	0.17	0.17	0.24	14.5	0.2	2200	1.1				
VW-1	08/27/93	0.00	17:41	0.36	0.36	0.52	10.5	0.5	3200	1.2				
VW-1	08/27/93	0.00	22:18	0.55	0.55	0.80	8.0	0.5	4000	1.6				
VW-1	08/28/93	1.00	09:52	0.03	1.03	1.49	4.0	0.5	5200	1.7		Trend of O2/	New	
												Time	x-values	0.01481
VW-2	08/27/93	0.00	09:24	0.00	0.00	0.00	20.8	0.5	300	0.0		20.8	0	
VW-2	08/27/93	0.00	10:18	0.04	0.04	0.05	20.0	0.4	240	0.0		20.0592593	0.05	
MPA-5	08/27/93	0.00	09:15	0.00	0.00	0.00	18.8	2.8	800	0.28		18.8	0	0.01818
MPA-5	08/27/93	0.00	09:59	0.03	0.03	0.04	18.0	3.5	700	0.21		18.0727273	0.04	
MPA-5	08/29/93	2.00	09:35	0.01	2.01	2.90	16.0	5.2	NS	NS	After injecting at VW overnight.			
MPA-10	08/27/93	0.00	09:11	0.00	0.00	0.00	19.0	0.2	720	1.4		Trend of O2/	New	k
MPA-10	08/27/93	0.00	09:57	0.03	0.03	0.05	17.9	0.2	1000	1.5		Time	x-values	0.01986
MPA-10	08/27/93	0.00	11:08	0.08	0.08	0.12	15.6	0.2	1400	1.3		18.4549339	0	
MPA-10	08/27/93	0.00	13:11	0.17	0.17	0.24	12.8	0.2	1700	1.1		2.96295352	0.78	
MPA-10	08/27/93	0.00	17:33	0.35	0.35	0.50	9.0	0.5	2400	1.4				
MPA-10	08/27/93	0.00	22:07	0.54	0.54	0.78	6.2	0.5	3000	1.8				
MPA-10	08/28/93	1.00	09:43	0.02	1.02	1.47	1.8	0.3	7000	1.9				
MPA-10	08/29/93	2.00	09:39	0.02	2.02	2.91	11.0	0.6	NS	NS	After injecting at VW overnight.			
MPA-14	08/27/93	0.00	09:07	0.00	0.00	0.00	19.0	0.3	400	1.4		Trend of O2/	New	k
MPA-14	08/27/93	0.00	09:53	0.03	0.03	0.05	17.8	0.3	850	1.5		Time	x-values	0.01744
MPA-14	08/27/93	0.00	11:05	0.08	0.08	0.12	15.5	0.3	1000	1.3		18.0225215	0	
MPA-14	08/27/93	0.00	13:07	0.17	0.17	0.24	12.4	0.3	1600	1.3		4.42098077	0.78	
MPA-14	08/27/93	0.00	17:29	0.35	0.35	0.50	8.9	0.5	2000	1.4				
MPA-14	08/27/93	0.00	22:09	0.54	0.54	0.78	5.1	0.5	2800	1.4				
MPA-14	08/28/93	1.00	09:38	0.02	1.02	1.47	1.8	0.4	4000	1.9				
MPA-14	08/28/93	1.00	13:32	0.18	1.18	1.71	20.4	0.5	NS	NS	After 1 hour perm.	Trend of O2/	New	k
												Time	x-values	-0.0351
MPB-5	08/27/93	0.00	08:53	0.00	0.00	0.00	19.1	2.6	580	0.31		19.1	0	
MPB-5	08/27/93	0.00	09:50	0.04	0.04	0.06	19.3	2.5	360	0.24		20.5035088	0.4	
MPB-5	08/29/93	2.00	09:42	0.03	2.03	2.93	19.5	2.6	NS	NS				
MPB-10	08/27/93	0.00	08:50	0.00	0.00	0.00	19.0	1.4	10000	0.48		19	0	-0.0357
MPB-10	08/27/93	0.00	09:46	0.04	0.04	0.06	19.2	1.6	7000	0.27		20.4285714	0.4	
MPB-10	08/29/93	2.00	09:45	0.04	2.04	2.94	19.2	1.8	NS	NS				

MPB-14	08/27/93	0.00	08:46	0.00	0.00	0.00	19.2	0.3	200	1.7		Trend of O2/	New	k	
MPB-14	08/27/93	0.00	09:43	0.04	0.04	0.06	17.8	0.2	520	1.5		Time	x-values	0.01801	
MPB-14	08/27/93	0.00	10:47	0.08	0.08	0.12	15.5	0.5	1000	1.1		18.1836338	0		
MPB-14	08/27/93	0.00	12:46	0.17	0.17	0.24	12.6	0.2	1000	1.4		3.77171567	0.8		
MPB-14	08/27/93	0.00	17:23	0.36	0.36	0.52	8.0	0.5	1400	1.4					
MPB-14	08/27/93	0.00	22:03	0.55	0.55	0.80	4.8	0.5	2100	1.7					
MPB-14	08/28/93	1.00	09:34	0.03	1.03	1.49	1.5	0.5	2800	1.7					
MPB-14	08/28/93	1.00	13:33	0.20	1.20	1.73	18.5	0.5	NS	NS	After 1 hour perm.				
MPC-5	08/27/93	0.00	08:40	0.00	0.00	0.00	20.1	0.5	240	0.47		20.1	0	0	
MPC-5	08/27/93	0.00	09:40	0.04	0.04	0.06	20.1	0.5	270	0.28		20.1	0.4		
MPC-5	08/29/93	2.00	09:49	0.05	2.05	2.95	21.0	0.5	NS	NS					
MPC-10	08/27/93	0.00	08:37	0.00	0.00	0.00	20.2	0.3	280	0.70		Trend of O2/	New	k	
MPC-10	08/27/93	0.00	09:36	0.04	0.04	0.06	20.5	0.2	100	0.22		Time	x-values	-0.0001	
MPC-10	08/27/93	0.00	10:36	0.08	0.08	0.12	20.0	0.0	120	0.27		20.249446	0		
MPC-10	08/27/93	0.00	12:37	0.17	0.17	0.24	20.5	0.2	NS	NS		20.4314227	1.56		
MPC-10	08/27/93	0.00	17:20	0.36	0.36	0.52	20.0	0.5	330	0.14					
MPC-10	08/27/93	0.00	21:59	0.56	0.56	0.80	20.5	0.5	120	0.14					
MPC-10	08/28/93	1.00	09:29	0.04	1.04	1.49	20.5	0.5	180	0.0					
MPC-10	08/29/93	2.00	09:51	0.05	2.05	2.95	20.7	0.5	NS	NS					
MPC-14	08/27/93	0.00	08:32	0.00	0.00	0.00	6.1	5.2	8200	1.6		Trend of O2/	New	k	
MPC-14	08/27/93	0.00	09:34	0.04	0.04	0.06	2.9	5.2	4800	1.4		Time	x-values	-0.0006	
MPC-14	08/27/93	0.00	10:42	0.09	0.09	0.13	1.5	NS	3100	1.3		2.3771814	0		
MPC-14	08/27/93	0.00	12:33	0.17	0.17	0.24	0.5	5.5	3000	1.4		3.49693915	1.74		
MPC-14	08/27/93	0.00	17:16	0.36	0.36	0.52	0.5	6.5	4400	1.5					
MPC-14	08/28/93	1.00	13:34	0.21	1.21	1.74	4.5	5.0	NS	NS					

Ellsworth AFB – Area D – Initial Biodegradation Rate Calculations

enter data | calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: VW–1
K_o = max. observed rate 0.0167 %/min.
w = moisture content 15 %

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity:	*n* =	0.35
Unit weight (dry):	^{g}d =	1.72
Void ratio:	*e = n/1–n* =	0.54
Specific gravity:	G =	2.65

Calculate A = Air filled volume (V_a)/unit wt.
Solving for 1 liter of soil

a) $V_v = n * 1$ L
V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$
S_r = 0.74 S_r = degree of saturation

c) $V_w = S_r \times V_v$
V_w = 0.26 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$
V_a = 0.09 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w)$ = 2 kg/l soil

f) A = V_a/Bulk density = 0.045 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 1511.3 mg TPH/year

Ellsworth AFB – Area D – Initial Biodegradation Rate Calculations

enter data	calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPA–10

K_o = max. observed rate 0.0199 %/min.

w = moisture content 13 %

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity:	n =	0.35
Unit weight (dry):	^{g}d =	1.72
Void ratio:	$e = n/1-n$ =	0.54
Specific gravity:	G =	2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1\ L$

V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$

S_r = 0.64 S_r = degree of saturation

c) $V_w = S_r \times V_v$

V_w = 0.22 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$

V_a = 0.13 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w)$ = 1.9 kg/l soil

f) A = V_a/Bulk density = 0.068 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 2717.6 mg TPH/year

Ellsworth AFB – Area D – Initial Biodegradation Rate Calculations

enter data	calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPA–14

K_o =	max. observed rate	0.0170	%/min.
w =	moisture content	15	%

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity:	*n* =	0.35
Unit weight (dry):	^{g}d =	1.72
Void ratio:	*e = n/1–n* =	0.54
Specific gravity:	G =	2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1$ L

V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$

S_r = 0.74 S_r = degree of saturation

c) $V_w = S_r \times V_v$

V_w = 0.26 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$

V_a = 0.09 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w)$ = 2 kg/l soil

f) A = V_a/Bulk density = 0.045 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 1539.4 mg TPH/year

Ellsworth AFB – Area D – Initial Biodegradation Rate Calculations

enter data | calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPB–14

K_o = max. observed rate 0.0180 %/min.

w = moisture content 15 %

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity:	*n* =	0.35
Unit weight (dry):	^{g}d =	1.72
Void ratio:	*e = n/1−n* =	0.54
Specific gravity:	G =	2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1$ L

V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$

S_r = 0.74 S_r = degree of saturation

c) $V_w = S_r \times V_v$

V_w = 0.26 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$

V_a = 0.09 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w)$ = 2 kg/l soil

f) A = V_a/Bulk density = 0.045 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 1630 mg TPH/year

6-Month Respiration Test
Area D
Ellsworth AFB, SD

Monitoring Point	Date	Days Elapsed (frac. days)	Time	Hrs elapsed (fractional days)	Days Elapsed	Elapsed Time (min. x 1000)	O2%	CO2%	Total Hydro-carbon	Comments	Trend of O2/ Time	New x-values	k
MPA-5	04/12/94	0.00	08:44	0.00	0.00	0.00	21.0	0.50	120		20.325358	0	0.0001421
MPA-5	04/12/94	0.00	12:00	0.14	0.14	0.20	19.5	0.40	130		19.915978	2.88	
MPA-5	04/12/94	0.00	17:45	0.38	0.38	0.55	20.4	0.40	224				
MPA-5	04/13/94	1.00	09:20	0.03	1.03	1.48	20.0	0.60	56				
MPA-5	04/14/94	2.00	08:44	0.00	2.00	2.88	20.0	0.60	44				
MPA-10	04/12/94	0.00	08:46	0.00	0.00	0.01	20.8	0.30	1,600		20.455113	0	0.0002293
MPA-10	04/12/94	0.00	12:02	0.14	0.14	0.20	19.6	0.02	1,600		19.792339	2.89	
MPA-10	04/12/94	0.00	17:46	0.38	0.38	0.55	20.9	0.40	1,960				
MPA-10	04/13/94	1.00	09:25	0.03	1.03	1.49	20.0	0.30	1,740				
MPA-10	04/14/94	2.00	08:47	0.00	2.00	2.89	19.8	0.55	2,400				
MPA-14	04/12/94	0.00	08:49	0.01	0.01	0.01	20.9	0.09	360		20.904676	0	0.0014431
MPA-14	04/12/94	0.00	12:04	0.14	0.14	0.20	20.9	0.09	400		16.734075	2.89	
MPA-14	04/12/94	0.00	17:50	0.38	0.38	0.55	20.1	0.09	460				
MPA-14	04/13/94	1.00	09:30	0.03	1.03	1.49	18.2	0.20	520				
MPA-14	04/14/94	2.00	08:51	0.01	2.01	2.89	17.0	0.50	880				
MPB-5	04/12/94	0.00	08:50	0.01	0.01	0.01	20.0	1.10	2,200		20.208348	0	0.0001828
MPB-5	04/12/94	0.00	12:06	0.14	0.14	0.21	20.4	0.90	1,000		19.678253	2.9	
MPB-5	04/12/94	0.00	17:50	0.38	0.38	0.55	20.3	0.90	660				
MPB-5	04/13/94	1.00	09:31	0.04	1.04	1.49	19.6	0.90	380				
MPB-5	04/14/94	2.00	08:55	0.01	2.01	2.90	19.8	0.75	160				
MPB-10	04/12/94	0.00	08:52	0.01	0.01	0.01	19.2	2.50	6,200		19.440209	0	0.0000002
MPB-10	04/12/94	0.00	12:08	0.14	0.14	0.21	19.3	2.20	3,000		19.439622	2.9	
MPB-10	04/12/94	0.00	17:52	0.38	0.38	0.55	20.1	1.80	5,800				
MPB-10	04/13/94	1.00	09:32	0.04	1.04	1.49	19.1	1.90	2,400				
MPB-10	04/14/94	2.00	08:57	0.01	2.01	2.90	19.5	1.20	1,000				
MPB-14	04/12/94	0.00	09:00	0.01	0.01	0.02	20.9	0.50	4,600		20.922661	0	0.0017990
MPB-14	04/12/94	0.00	12:09	0.15	0.15	0.21	20.8	0.02	4,600		15.705627	2.9	
MPB-14	04/12/94	0.00	17:54	0.38	0.38	0.55	19.7	0.70	4,400				
MPB-14	04/13/94	1.00	09:34	0.04	1.04	1.49	18.1	0.70	6,000				
MPB-14	04/14/94	2.00	09:00	0.01	2.01	2.90	15.8	0.80	8,400				
MPC-5	04/12/94	0.00	09:00	0.01	0.01	0.02	5.4	7.00	4,200		6.7649065	0	-0.0016147
MPC-5	04/12/94	0.00	12:09	0.15	0.15	0.21	4.2	5.20	3,200		11.463694	2.91	
MPC-5	04/12/94	0.00	17:56	0.39	0.39	0.56	11.8	6.20	2,600				
MPC-5	04/13/94	1.00	09:37	0.04	1.04	1.50	10.7	6.50	3,800				
MPC-5	04/14/94	2.00	09:05	0.02	2.02	2.91	10.1	7.50	4,400				
MPC-10	04/12/94	0.00	09:02	0.02	0.02	0.02	4.2	8.90	5,900		2.1202059	0	0.0005968
MPC-10	04/12/94	0.00	12:10	0.15	0.15	0.21	1.1	17.00	6,000		0.3834861	2.91	
MPC-10	04/12/94	0.00	17:58	0.39	0.39	0.56	0.2	18.10	7,600				
MPC-10	04/13/94	1.00	09:38	0.04	1.04	1.50	1.3	10.30	7,200				
MPC-10	04/14/94	2.00	09:08	0.02	2.02	2.91	0.7	12.00	9,000				

MPC-14	04/12/94	0.00	09:05	0.02	0.02	0.03	12.5	5.00	5,100		10.521193	0	0.0039159		
MPC-14	04/12/94	0.00	12:15	0.15	0.15	0.22	10.0	5.00	6,000		-0.8741938	2.91			
MPC-14	04/12/94	0.00	18:00	0.39	0.39	0.56	7.0	7.30	6,800						
MPC-14	04/13/94	1.00	09:40	0.04	1.04	1.50	2.0	7.10	8,200						
MPC-14	04/14/94	2.00	09:11	0.02	2.02	2.91	0.7	9.00	8,800						

Ellsworth AFB – Area D – 6 Month Biodegradation Rate Calculations

enter data | calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPA–10

K_o =	max. observed rate	0.0002	%/min.
w =	moisture content	13	%

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity:	*n* =	0.35
Unit weight (dry):	^{g}d =	1.72
Void ratio:	*e = n/1–n* =	0.54
Specific gravity:	G =	2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1\ L$

V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$

S_r = 0.64 S_r = degree of saturation

c) $V_w = S_r \times V_v$

V_w = 0.22 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$

V_a = 0.13 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w)$ = 1.9 kg/l soil

f) A = V_a/Bulk density = 0.068 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 27.4 mg TPH/year

Ellsworth AFB – Area D – 6 Month
Biodegradation Rate Calculations

enter data | calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPA–14

K_o =	max. observed rate	0.0014	%/min.
w =	moisture content	15	%

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity:	*n* =	0.35
Unit weight (dry):	^{g}d =	1.72
Void ratio:	*e = n/1–n* =	0.54
Specific gravity:	G =	2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1$ L

V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$

S_r = 0.74 S_r = degree of saturation

c) $V_w = S_r \times V_v$

V_w = 0.26 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$

V_a = 0.09 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w)$ = 2 kg/l soil

f) A = V_a/Bulk density = 0.045 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 126.8 mg TPH/year

Ellsworth AFB – Area D – 6 Month Biodegradation Rate Calculations

enter data | calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPB–14

K_o = max. observed rate 0.0018 %/min.

w = moisture content 15 %

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity:	n =	0.35
Unit weight (dry):	^{g}d =	1.72
Void ratio:	$e = n/1-n$ =	0.54
Specific gravity:	G =	2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1$ L

V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$

S_r = 0.74 S_r = degree of saturation

c) $V_w = S_r \times V_v$

V_w = 0.26 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$

V_a = 0.09 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w)$ = 2 kg/l soil

f) $A = V_a/\text{Bulk density}$ = 0.045 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 163 mg TPH/year

1-Year Respiration Test

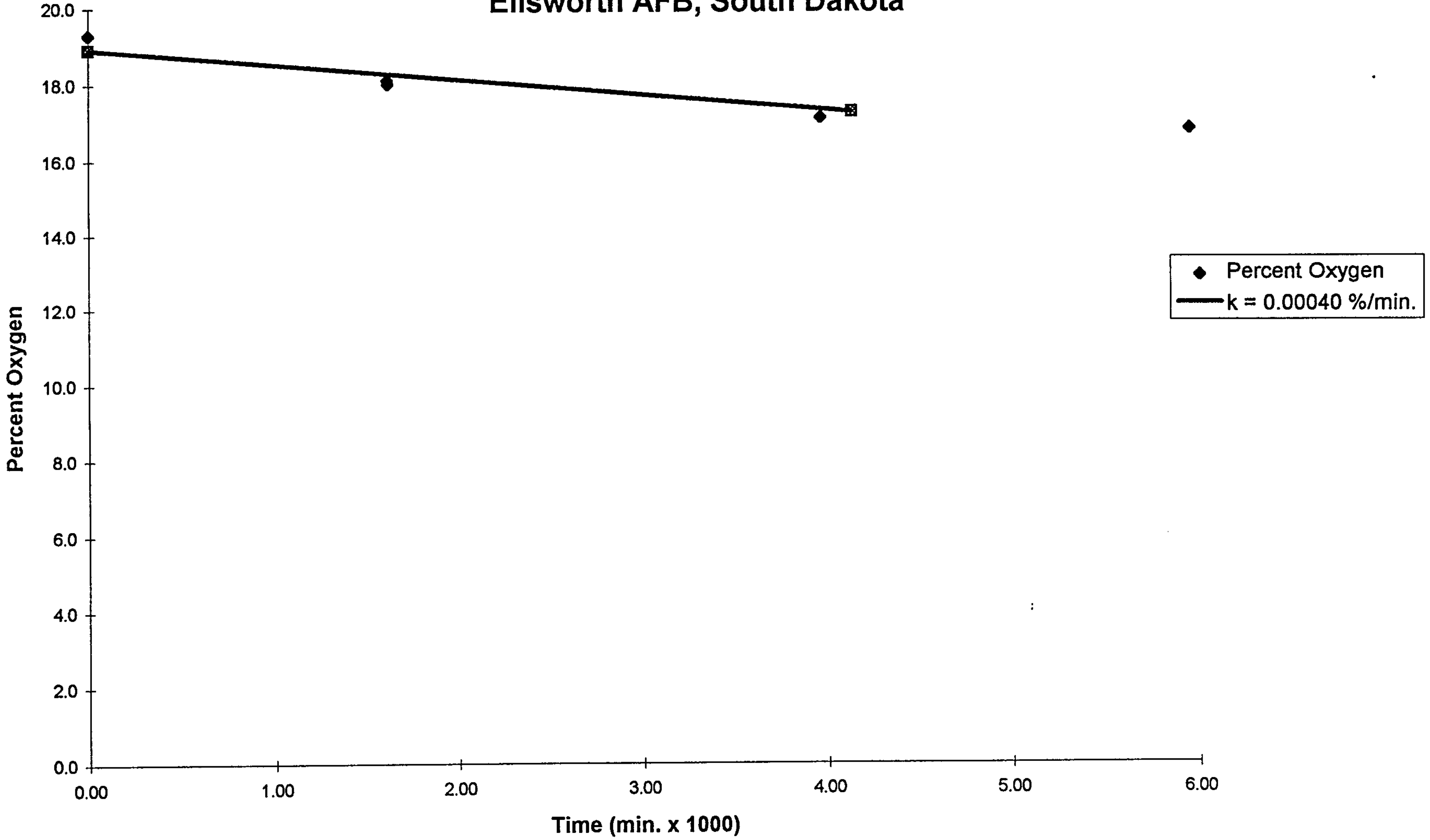
Area D

Ellsworth AFB, South Dakota

Monitoring Point	Date	Days Elapsed (frac. days)	Time	Hrs. elapsed (fractional days)	Days Elapsed	Elapsed Time (min. x 1000)	% 0_2	% $C0_2$	Total Hydro-carbon	Comments	Trend of O_2/ Time	New x-values	K_o
VW-1	8/24/94	0	14:30	0.00	0.00	0.00	19.3	0.70	120		18.9115	0	0.0004
VW-1	8/25/94	1	17:24	0.12	1.12	1.61	18.1	2.90	220		17.259289	4.13	
VW-1	8/25/94	1	17:27	0.12	1.12	1.62	18.0	2.50	220	Resample			
VW-1	8/27/94	3	8:30	-0.25	2.75	3.96	17.1	3.20	300				
VW-1	8/28/94	4	17:34	0.13	4.13	5.94	16.8	1.30	340				
MPA-10	8/24/94	0	14:35	0.00	0.00	0.00	20.0	0.50	2000		19.89641	0	0.000728
MPA-10	8/24/94	0	18:11	0.08	0.08	0.11	19.9	0.60	2100		15.325105	6.28	
MPA-10	8/25/94	1	8:10	-0.02	0.98	1.41	19.1	0.4	1800				
MPA-10	8/25/94	1	17:30	0.00	1.00	1.44	18.1	0.60	2000				
MPA-10	8/26/94	2	8:30	0.13	2.13	3.07	17.8	0.50	1800				
MPA-10	8/27/94	3	8:35	0.36	3.36	4.83	17.0	0.50	1500				
MPA-10	8/28/94	4	17:36	0.36	4.36	6.28	14.9	0.50	1800				
MPA-14	8/24/94	0	14:33	0.00	0.00	0.00	20.8	0.00	18		20.495798	0	0.001613
MPA-14	8/24/94	0	18:09	0.43	0.43	0.61	20.1	0.10	140		10.267022	6.34	
MPA-14	8/25/94	1	8:14	0.01	1.01	1.46	18.0	0.10	200				
MPA-14	8/25/94	1	17:36	0.40	1.40	2.02	16.8	0.20	240				
MPA-14	8/26/94	2	8:35	0.03	2.03	2.92	15.2	0.20	300				
MPA-14	8/27/94	3	8:40	0.03	3.03	4.36	13.1	0.50	400				
MPA-14	8/28/94	4	17:39	0.40	4.40	6.34	10.9	0.30	420				
MPB-14	8/24/94	0	14:40	0.00	0.00	0.00	20.9	0.00	120		20.597807	0	0.002172
MPB-14	8/24/94	0	18:16	0.15	0.15	0.22	20.2	0.10	360		7.6931095	5.94	
MPB-14	8/25/94	1	8:19	-0.26	0.74	1.06	18.5	0.20	780				
MPB-14	8/25/94	1	17:45	0.13	1.13	1.63	16.9	0.20	1000				
MPB-14	8/26/94	2	8:39	-0.25	1.75	2.52	14.4	0.50	1200				
MPB-14	8/27/94	3	8:45	-0.25	2.75	3.97	12.0	0.50	1200				
MPB-14	8/28/94	4	17:42	0.13	4.13	5.94	8.0	0.50	1800				
MPC-10	8/24/94	0	14:43	0.00	0.00	0.00	20.2	0.10	86		19.792279	0	0.000656

MPC-10	8/25/94	1	17:50	0.29	1.29	1.86	18.2	2.60	200		16.338244	5.26	
MPC-10	8/26/94	2	8:42	0.43	2.43	3.50	17.0	2.50	220				
MPC-10	8/27/94	3	8:50	0.65	3.65	5.26	16.8	4.00	220				

Figure 1.0
1-Year Respiration Test
Area D: VW-1
Ellsworth AFB, South Dakota



ELLS-D1Y.XLS

Figure 1.1
1-Year Respiration Test
Area D: MPA-10
Ellsworth AFB, South Dakota

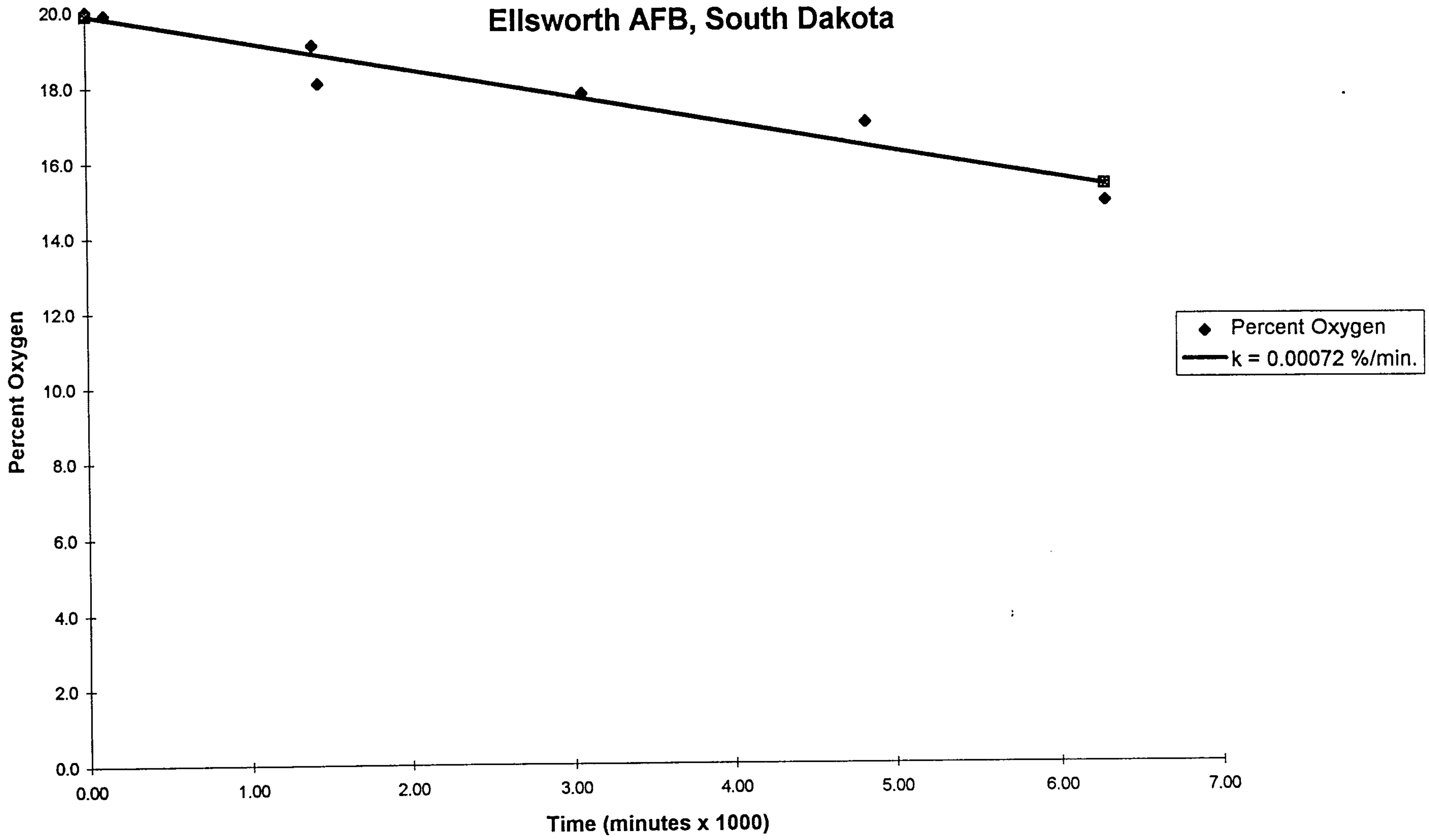


Figure 1.2
1-Year Respiration Test
Area D: MPA-14
Ellsworth AFB, South Dakota

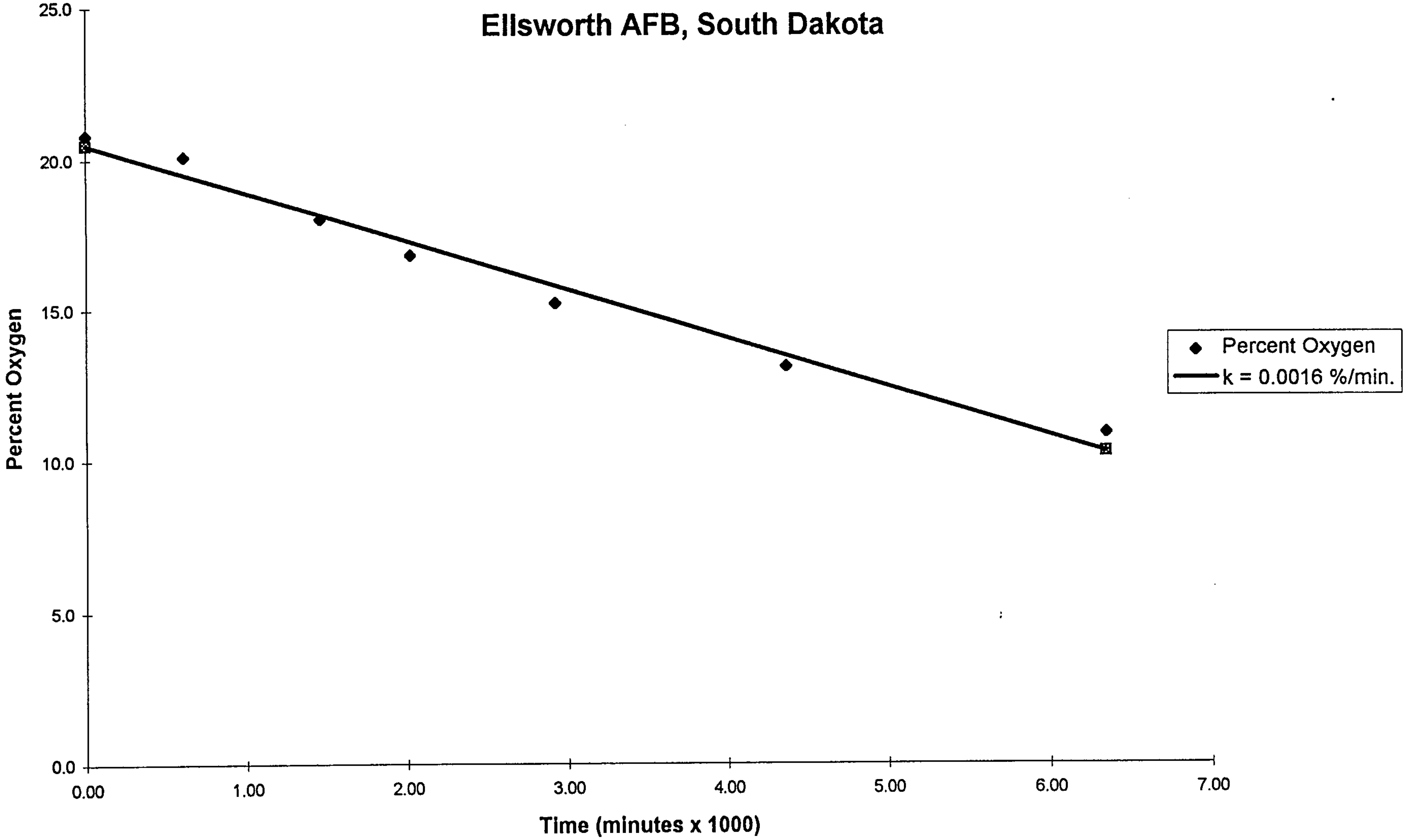


Figure 1.3
1-Year Respiration Test
Area D: MPB-14
Ellsworth AFB, South Dakota

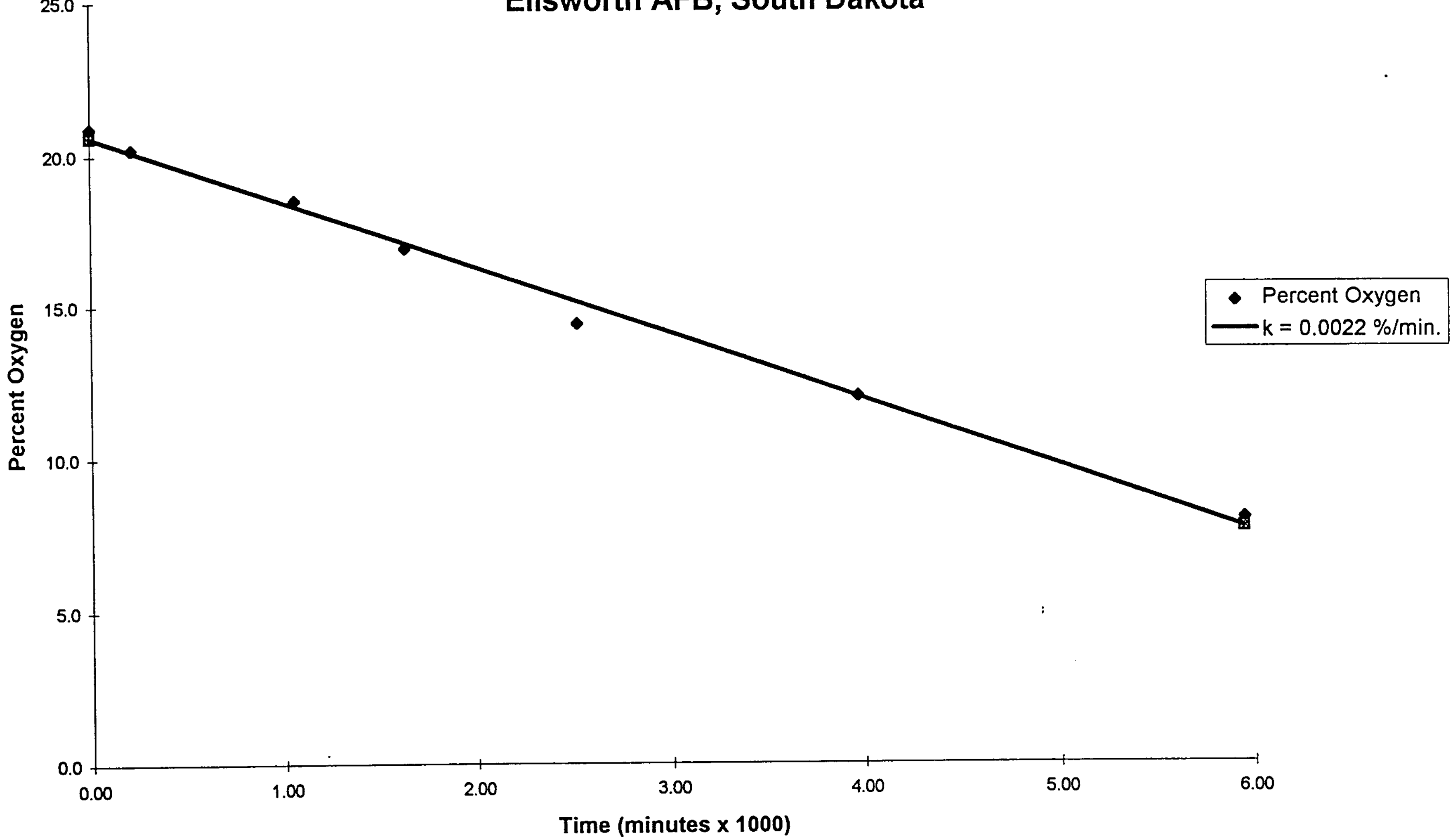
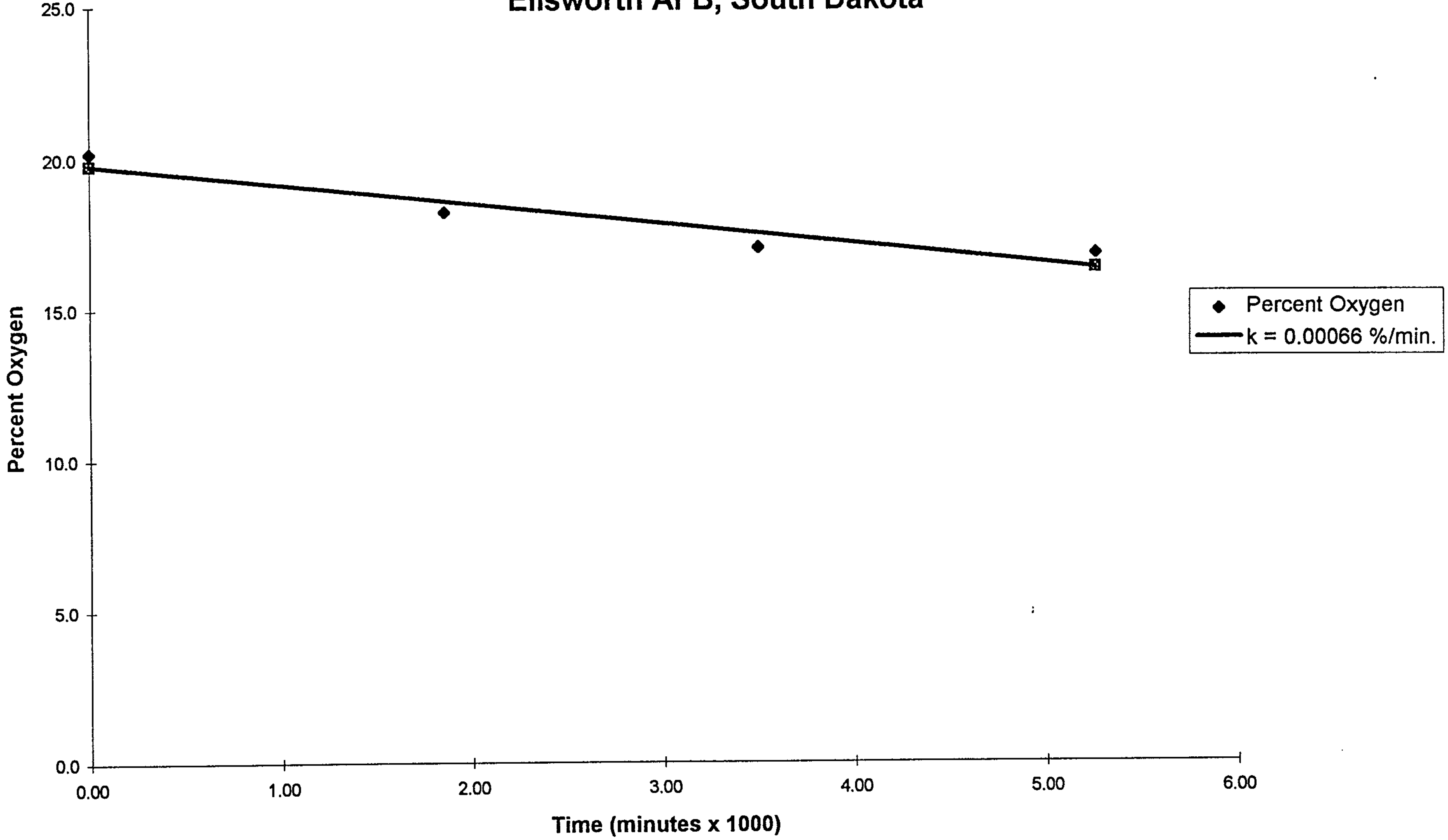


Figure 1.4
1-Year Respiration Test
Area D: MPC-10
Ellsworth AFB, South Dakota



ELLS-D1Y.XLW

Ellsworth AFB – Area D – 1 year
Biodegradation Rate Calculations

enter data | calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: VW–1 K_o = max. observed rate 0.0004 %/min.
w = moisture content 20 %

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity: $n =$ 0.35
Unit weight (dry): $^{g}d =$ 1.72
Void ratio: $e = n/1-n =$ 0.54
Specific gravity: $G =$ 2.65

Calculate A = Air filled volume (V_a)/unit wt.
Solving for 1 liter of soil

a) $V_v = n * 1$ L
$V_v =$ 0.35 liters V_v = void volume

b) $S_r = Gw/e$
$S_r =$ 0.98 S_r = degree of saturation

c) $V_w = S_r \times V_v$
$V_w =$ 0.34 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$
$V_a =$ 0.01 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w) =$ 2.1 kg/l soil

f) $A = V_a$/Bulk density = 0.005 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 4 mg TPH/year

Ellsworth AFB – Area D – 1 year
Biodegradation Rate Calculations

enter data | calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPA–10

K_o = max. observed rate 0.0007 %/min.

w = moisture content 13 %

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity: n = 0.35

Unit weight (dry): ^{g}d = 1.72

Void ratio: $e = n/1-n$ = 0.54

Specific gravity: G = 2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1$ L

V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$

S_r = 0.64 S_r = degree of saturation

c) $V_w = S_r \times V_v$

V_w = 0.22 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$

V_a = 0.13 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {^{g}w})$ = 1.9 kg/l soil

f) A = V_a/Bulk density = 0.068 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 99.9 mg TPH/year

Ellsworth AFB – Area D – 1 Year
Biodegradation Rate Calculations

enter data | calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPA–14 K_o = max. observed rate 0.0016 %/min.
w = moisture content 15 %

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity: $n =$ 0.35
Unit weight (dry): $^{g}d =$ 1.72
Void ratio: $e = n/1-n =$ 0.54
Specific gravity: G = 2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1$ L
$V_v =$ 0.35 liters V_v = void volume

b) $S_r = Gw/e$
$S_r =$ 0.74 S_r = degree of saturation

c) $V_w = S_r \times V_v$
$V_w =$ 0.26 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$
$V_a =$ 0.09 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {^{g}w})$ = 2 kg/l soil

f) A = V_a/Bulk density = 0.045 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 144.9 mg TPH/year

Ellsworth AFB – Area D – 1 Year
Biodegradation Rate Calculations

enter data	calculated data

Formula: $K_b = K_o \times 1/100\% \times A \times D_o \times C$ Where:

K_b = fuel biodegradation rate

K_o = O_2 utilization rate (%/min.)

A = volume of air/kg soil

D_o = O_2 density 1340 mg/L

C = Carbon/O_2 ratio for hexane mineralization = 1/3.5

Test Results: MPB–14

K_o = max. observed rate 0.0022 %/min.

w = moisture content 15 %

Assume: Soil properties for mixed grained sand Specify from Table 1.4 (Ref. Foundation Engineering, Peck, Hanson, and Thornburn, John Wiley Press, 1974)

Porosity:	*n* =	0.35
Unit weight (dry):	^{g}d =	1.72
Void ratio:	*e = n/1−n* =	0.54
Specific gravity:	G =	2.65

Calculate A = Air filled volume (V_a)/unit wt.

Solving for 1 liter of soil

a) $V_v = n * 1\ L$

V_v = 0.35 liters V_v = void volume

b) $S_r = Gw/e$

S_r = 0.74 S_r = degree of saturation

c) $V_w = S_r \times V_v$

V_w = 0.26 liters V_w = volume of water

d) $V_a = V_v - V_{vw}$

V_a = 0.09 liters V_w = volume of water

e) Bulk density = $^{g}d + (V_w \times {}^{g}w)$ = 2 kg/l soil

f) A = V_a/Bulk density = 0.045 l air/kg soil

$K_b = K_o \times 1/100\% \times A \times D_o \times C \times$ 525,600 min/yr = 199.2 mg TPH/year

MW24 21.08' btoc ▽
MW23 17.57' ▽ btoc
MW18 15.45' ▽ btoc
MW31 18.11' ▽ btoc
MW17 19.00' ▽ btoc
MW30 21.03' ▽ btoc
MW26 34.64' ▽ btoc
MW 27 28.85' ▽ btoc
MW 15 26.2' ▽ btoc
MW 14 28.38' ▽ btoc
MW 19 27.14' ▽ btoc
MW 1 16.87' ▽ btoc
MW 40 17.00' ▽ btoc
MW 32 23.00' ▽ btoc

10/11/95

13:45 Arrive @ Base & get pass from main gate

13:50 Ved in w/ B.H. McCallum
(He would like an additional copy of [illegible] [illegible] doc.)

14:15 Arrive @ "site" w/ escort "Jermey"

14:20 Checking MW-6 & surrounding wells for free product (see next page - results)

MW-6 open - distinct fuel odor

(note weather: clear, breezy ~ 10mph from SW
~65°F)

MW-20 no fuel odor

15:30 4" well keys don't work but w/ some giggling well lids can be worked off side ways; however can't relock 4" well cover lid, just putting back in place.

Well	Depth to product (ft BTOC)	Depth to H2O (ft BTOC)
MW-6	21 1 3/4"	22' 9"
MW-20	none	22' 6 3/8"
MW-39	—	19' 2"
MW-22	—	24' 3 3/8"
MW-5	—	19' 7 3/8"
MW-35	—	21' 1 3/8"
MW-34	—	22' 6"
MW-36	—	23' 4 1/2"
MW-37	—	21' 7 1/2"
MW-33	—	23' 3 7/8"
MW-15	—	24' 5 7/8"
MW14	—	27' 11 3/8"
MW-19	—	27' 0 1/8"
MW-32	—	22' 7 7/8"
MW-1	—	16' 8 5/8"
MW-40	—	16' 7 3/4"
MW-2	—	13' 4 7/8"
MW3	—	under water
MW 38	—	15' 8 1/2"
MW21	—	23' 0 3/4"
MW 13	—	under water
MW-16	—	12' 5"

~~[illegible]~~

* A new leak detection system is being installed @ Area D & several new monitoring wells appear to have been installed within the extents of the current plume. Contacted Bill McCollum & we are going to speak w/ Mark Wheeler of CE about new wells tomorrow.

~~Leave sit~~

18:30 Leave site will start balloon test 1st thing in am

10/12/95

07:30 Arrive at site & can't contact fuels to open gate. Head for environmental but Bill is not in yet.

08:00 Come back to site & fuels guy are at site

08:10 Set up on MW-6 for baildown test.

Tag ~~MW-6~~	well -	Product (ft BTOC)	Water (ft BTOC)
	MW-6	21' 2$\frac{1}{8}$"	22' 8$\frac{7}{8}$"

08:45 Finish bailing product from well Remove approximately 64 oz of product.

After product removed

	Product	Water
MW-6	~~23' 6$\frac{1}{8}$"~~ 23 6$\frac{1}{8}$"	~~22' 6$\frac{3}{8}$"~~ 23 6 $\frac{3}{8}$"

09:00 Work on KC-135 comments

		Product	Water
10:45	MW6	23' 4$\frac{3}{8}$"	23' 5$\frac{1}{2}$"

11:00 Lunch

12:30	MW6	23 3$\frac{3}{4}$	23' 5$\frac{1}{8}$"

14:00 Talk w/ Mark III Environmental (tank yank contractor) & they are going to accept our purge water for MW-5, MW-13, & MW-18.

15:00 Leave site will return @ 18:00 Go to Wal Mart for supplies

18:15 Return to site ✓ level in MW-6

	Product (ft BTOC)	Water (ft BTOC)
MW-6	23' 2$\frac{5}{8}$"	23' 4$\frac{1}{4}$"

22:15 Return to site ✓ MW-6

	Prod (ft BTOC)	Water (feet BTOC)
MW6	23' 2$\frac{1}{8}$"	~~23' 3$\frac{3}{4}$~~ 23' 3$\frac{3}{4}$"

10/13/95

0800 ~~Return~~ Arrive at Site

Windy & Cloudy · winds out of north at ~ 60 mph - sampling is going to be fun

Reading @ MW-6

	Prod (ft BTOC)	Water (ft BTOC)
MW-6	23' 1"	23' 2 3/4"

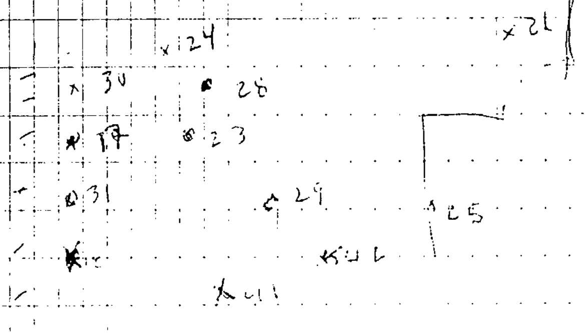
08:30 Having difficult time collecting sample/bailing wells & recording readings in high winds

∴ Going to collect remaining H_2O levels & hope winds die down abit.

09:00 H_2O Levels for wells outside Area D

see next Page

Well #	Product	Water (ft BTOC)
MW 18	—	14' 7 1/4"
MW 31	—	16' 8 3/4"
MW 17	—	17' 7 3/8"
MW 30	—	19' 7 1/2"
MW 24	—	19' 8 1/2"
MW 28	—	18' 1"
MW 23	—	1[illegible]
MW 21	—	1[illegible]
MW 41	—	11' 9 1/2"
MW 42	—	under water No Meas.
MW 25	—	Could not locate *
MW 26	—	23' 5 7/8"
MW 27	—	27' 4 3/4"



MW 23 well box needs repairs

* MW 25 - appears to have been abandoned only a recession in ground where well should be!

11:00 Leave site for lunch

12:00 Return to site

Site lock'd & no one answering @ fuel

∴ set up to sample MW-18.

	Water surface	TD
Tag	14' 7 3/8"	29' 1 3/8"

Total volume (casing) = 2.3 gal

	Temp(° C)	PH	cond (picosiemens)
Initial:	11.9	7.4	—
(1½ cv) ½ purge:	10.6	7.5	—
3 cv purge:	10.5	7.4	—

Collect 3 VOAs

[illegible]

14:00 Reach fuels & they open site

	Prod	Water (Ft BTOC)
MW-6	23' 0 3/4"	23' 2 1/2"

14:30 Set up on MW 5 for Sampling

	GW	TD
Tag	19 7 1/2	29 0 1/8

Casing Volume = 1.6 gal

	Temp(°C)	PH	Cond (picoS)
Initial:	10.8	7.5	—
			—
½ purge vol:	10.6	7.1	—
full purge vol:	10.7	7.1	—

15:30 Take reading from MW-6

	Prod	Water (Ft BTOC)
MW-6	23' 0 3/8	23' 2 1/4"

16:00 ✓ in w/ Bill @ CEV & inform him of test results

16:15 Leave site for Fed/Ex

Baildown Test Record Sheet

Site: Area D Ellsworth AFB

Well Identification: MW-6

Well Diameter (OD/ID): 2" PVC

Date at Start of Test: 10/12/95

Time at Start of Test: 08:15

Sampler's Initials: AJR

Initial Readings

Initial reading before bail down

Depth to Groundwater (ft)	Depth to LNAPL (ft)	LNAPL Thickness (ft)	Total Volume Bailed ~~(L)~~ (oz)
22' 8 7/8"	21' 2 1/8"	1' 6 3/4"	~ 64

Test Data

Initial reading after Bail down →

10/13/95 →

Sample Collection Time	Depth to Groundwater (ft)	Depth to LNAPL (ft)	LNAPL Thickness (ft)
08:45	23' 6 3/8"	23' 6 1/8"	1/4"
10:45	23' 4 3/8"	23' 5 1/2"	1 1/8"
13:30	23' 5 1/8"	23' 3 3/4	1 3/8"
18:15	23' 4 1/4"	23' 2 5/8"	1 5/8"
22:15	23' 2 1/8"	23' 3 3/4"	1 5/8"
0805	23' 2 3/4"	23' 1"	1 3/4"
14:00	23' 0 3/4"	23' 2 1/2"	1 3/4"
15:30	23 0 3/8"	23' 2 1/4"	1 7/8"

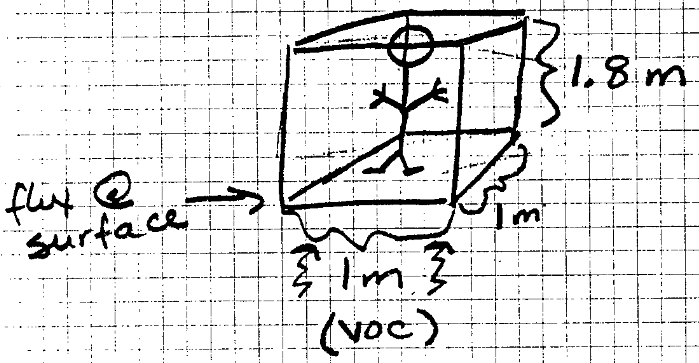
Figure 9. Typical Baildown Test Record Sheet

PARSONS Calculation Sheet

Rev	By	Date	Ck	Date	Title
0	LAB	11/30	RAF	12/1/95	Calculation of above-ground VOC Conc. based on soil flux data + simple box diffusion
					Author L. Benson Sheet 1 Of 1

Assumptions:

- no atmospheric dispersion
- worker exposure time = 8 hours
- breathing height = 6 feet



Data:

Xylenes 11.1 ug/m²-min

$$C = (C_{flux})\left(\frac{mg}{1000\,ug}\right)\left(\frac{60\,min}{hr}\right)\left(\frac{8\,hr}{workday}\right)\left(\frac{1}{1.8\,m}\right)$$

$$C = \left(\frac{11.1\,ug}{m^2\text{-}min}\right)\left(\frac{mg}{1000\,ug}\right)\left(\frac{60\,min}{hr}\right)(8\,hr)\left(\frac{1}{1.8\,m}\right)$$

$$C = 2.96\ \frac{mg}{m^3}$$ (max. exp. conc assuming no dispersion, limited movement)

APPENDIX G

RISK-BASED REMEDIAL CRITERIA

APPENDIX G
UNLIMITED LAND USE TARGET CONCENTRATIONS FOR SOIL
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Exposure Assumptions: Unlimited Land Use; Pathway Specific **Calculations**

INCIDENTAL INGESTION OF SOIL PARTICULATES

VARIABLES IN CARCINOGENIC EQUATION

ATc = Averaging Time for Carcinogens (yrs)	70
EF = Exposure Frequency (dys/yr)	350
IF = Soil Ingestion Factor (mg-yr/kg-d)	114
TR = Target risk	0.000001 (1x10^{-6})
SFo = Oral Slope Factor (kg-dy/mg)	chem-specific
Benzene	0.029

Carcinogenic Chemical Target Concentration Equation:

C = (TR * ATc * 365d/yr)/(SFo*10-6kg/mg*EF*IF)

VARIABLES IN NONCARCINOGENIC EQUATION

ATn = Averaging Time for Noncarcinogens (dys)	10
BW = Body Weight (kg)	15
EF = Exposure Frequency (dys/yr)	350
ED = Exposure Duration (yr)	10
IRw = Workday Soil Ingestion Rate (mg/dy)	200
THQ = Target Hazard Quotient	1
RfDo = Oral Reference Dose (mg/kg-dy)	chem-specific
Toluene	0.2
Ethylbenzene	0.1
Total Xylenes	2
Naphthalene	0.04

Noncarcinogenic Chemical Target Concentration Equation:

C = (THQ * BW * ATn*365d/yr)/(1/RfDo*10-6kg/mg*EF*ED*IR)

Soil COPC	Unlimited Land Use Noncarcinogenic Target Concentration	Unlimited Land Use Carcinogenic Target Concentration
Benzene	--	22
Toluene	1.6E+04	
Ethylbenzene	7.8E+03	
Total Xylenes	1.6E+05	

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APPENDIX G
UNLIMITED LAND USE TARGET CONCENTRATIONS FOR SOIL
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Exposure Assumptions: Unlimited Land Use; Pathway Specific		Calculations

INHALATION OF VOLATILES AND FUGITIVE DUST

VARIABLES IN CARCINOGENIC EQUATION	
ATc = Averaging Time for Carcinogens (yrs)	30
EF = Exposure Frequency (dys/yr)	350
ED = Exposure Duration (yr)	30
VF = Volatilization Factor	8.50E+03
Q/C = inverse mean conc. ((g/m^2)/(kg/m^3))	35.1
T = exposure interval (sec)	9.50E+08
D_{ei} = effective diffusivity = $D_i(\theta_a^{3.33}/n^2)$(cm^2/s)	0.007
θ_a = air-filled porosity	0.28
n = total soil porosity	0.43
$\alpha = (D_{ei}*\theta_a)/(\theta_a+\rho_s(1-\theta_a)/k_{as})$	0.000229
kas = soil-air partition coefficient = H/K_d	0.23
ρ_s = soil particle density (g/cm^3)	2.65
H = Henery's Law constant (unitles	chem-specific
benzene	0.232
$K_d = K_{oc}*f_{oc}$ (see Section 6)	1
ρ_b = dry soil bulk density (g/cm^3)	1.5
Target risk	0.000001 (1x10^{-6})
UFR (inhalation unit risk factor)(µg/	chem-specific
benzene	8.3E-06
PEF (particulate emmission factor) (m^3/kg)	6.79E+08
SFo = Oral Slope Factor (kg-dy/mg)	chem-specific
benzene	0.029

Carcinogenic Chemical Target Concentration Equation:

C = (TR * ATc * 365d/yr)/(URF*1000 µg/mg*EF*ED*((1/VF)+(1/PEF)))

Volatilization Factor

$VF = (Q/C)*(((3.14*\alpha*T)\hat{}1/2)/(2*D_{ei}*\theta_a*K_{as}))*10^{-4}$

VARIABLES IN NONCARCINOGENIC EQUATION	
ATn = Averaging Time for Noncarcinogens (dys)	10
EF = Exposure Frequency (dys/yr)	350
ED = Exposure Duration (yr)	10
VF (see above)	200
PEF (see above)	6.79E+08
THQ = Target Hazard Quotient	1
RfC = Inhalation reference concentration (mg/kg-dy)	chem-specific
Toluene	0.2
Ethylbenzene	0.1
Total Xylenes	2
Naphthalene	0.04

Noncarcinogenic Chemical Target Concentration Equation:

C = (THQ *ATn*365d/yr)/(EF*ED*((1/RFC)*((1/VF)+(1/PEF))))

Soil COPC	Unlimited Land Use Noncarcinogenic Target Concentration	Unlimited Land Use Carcinogenic Target Concentration
Benzene	--	0.5
Toluene	5.2E+02	
Ethylbenzene	2.6E+02	
Total Xylenes	3.2E+02	

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APPENDIX G
UNLIMITED LAND USE TARGET CONCENTRATIONS FOR SOIL
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Exposure Assumptions: Unlimited Land Use; Pathway Specific	Calculations

LEACHING TO GROUNDWATER

$C = C_w*(K_d+((\theta w+\theta a*H)/\rho b$

C_w = groundwater mcl (mg/L) (see Table 4.2)	
benzene	0.005
toluene	1
ethylbenzene	0.7
total xylenes	10
Kd = Koc*foc	
benzene	1
toluene	2.6
ethylbenzene	3.7
total xylenes	4.7
H = Henry's Law Constant (unitless)	
benzene	0.23
toluene	0.26
ethylbenzene	0.26
total xylenes	0.29
qa = air filled porosity	0.28
qw = water filled porosity	0.15

Soil COPC	Unlimited Land Use Noncarcinogenic Target Concentration	Unlimited Land Use Carcinogenic Target Concentration
Benzene	--	0.02
Toluene	5.0E+00	
Ethylbenzene	5.0E+00	
Total Xylenes	7.4E+01	

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APPENDIX G
UNLIMITED LAND USE TARGET CONCENTRATIONS FOR GROUNDWATER
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Exposure Assumptions: Unlimited Land Use; Pathway Specific	**Calculations**

INGESTION OF GROUNDWATER

VARIABLES IN CARCINOGENIC EQUATION

BW = body weight (kg)	15
TR = target risk	1E-06 ($1X10^{-6}$)
2L = 2 liters of water (liters)	2
SF_o = oral slope factor	chem-specific
benzene	0.029

VARIABLES IN NONCARCINOGENIC EQUATION

BW = body weight (kg)	15
RFD = oral reference dose	1E-06
toluene	0.2
ethylbenzene	0.1
total xylenes	2
naphthalene	0.004
2L = 2 liters of water (liters)	2

0.2 indicates that drinking water is 20% of total exposure

Carcinogenic Chemical Target Concentration Equation:

C = $(TR*BW*1000)/(SF_o*2L)$

Noncarcinogenic Chemical Target Concentration Equation:

C = $(RFD*BW*1000*0.2)/2L$

Groundwater COPC	Unlimited Land Use Noncarcinogenic Target Concentration	Unlimited Land Use Carcinogenic Target Concentration
Benzene	--	1.2
Toluene	1.4E+03	
Ethylbenzene	7.0E+00	
Total Xylenes	1.4E+04	
Naphthalene	2.8E+02	

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APPENDIX G
SITE-SPECIFIC TARGET CLAENUP CONCENTRATIONS FOR SOIL
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Exposure Assumptions: Cumulative for incidental ingestion, dermal contact, incidental inhalation, and leaching to soils

VARIABLES IN CARCINOGENIC EQUATION

TR = target cancer risk	0.000001 (1×10^{-6})
BW = adult body weight (kg) - default	70
ATc = averaging time (yrs) - default	70
EF = exposure frequency (days/yr) - site-specific	90
ED = exposure duration (yrs) - site-specific	10
IRs = soil ingestion rate (mg/day) - default	480
SA = skin surface area (cm^2) - default	5800
AF = skin-soil adherance ((mg/cm^2)/day) - default	1
DABS - absorption factor - default	0.25
IRa = fugitive dust ingestion rate (m^3/day) - default	31.2
VF = soil to air volatilization factor (m^3/kg) - site-specific	128205
PEF = particulate emission factor (m^3/kg) - default	4.39E+09

RFD_o, RFD_i, SF_o, AND SF_i AS DEFINED IN PREVIOUS GENERIC SSL CALC. SHEETS

VARIABLES IN NONCARCINOGENIC EQUATION

THQ = target hazard quotient - default	1
ATn = averaging time (yrs) - default	10

ALL OTHER VARIABLE ARE DEFINED AS ABOVE IN THE CARCINOGENIC EQUATION

VARIABLES IN LEACHING EQUATION

θw = water-filled porosity - site-specific	0.3
θa = air-filled porosity - site-specific	0.14
ρb = dry bulk density of soils - site-specific	2.34

ALL OTHER VARIABLE ARE DEFINED AS ABOVE IN PREVIOUS GENERIC SSL CALC. SHEETS

Calculations

Carcinogenic Chemical Target Concentration Equation:

$C = (TR * BW * ATc * 365d/yr)/((EF*ED)*((SFo*10\text{-}6kg/mg*IRs)+(SFo*SA*AF*10^{-6}*DABS)+(SFI*IRa*((1/VF)+1/(PEF)))))$

Noncarcinogenic Chemical Target Concentration Equation:

$C = (THQ * BW * ATn * 365d/yr)/((EF*ED)*(((1/RFDo)*10\text{-}6kg/mg*IRs)+((1/RFDi)*SA*AF*10^{-6}*DABS)+(((1/RFDi)SFI*IRa*((1/VF)+1/(PEF)))))$

Leaching Chemical Target Concentration Equation:

$C = C_w*((\rho b*K_d+\theta w+\theta a*H)/(\rho w*\theta \omega+\theta b))$

SOIL COC	SITE-SPECIFIC Noncarcinogenic Target Concentration	SITE-SPECIFIC Carcinogenic Target Concentration	SITE-SPECIFIC Leaching Target Concentration
Benzene	--	35 [a]	0.08 [a]
Toluene	1.8E+04		123
Ethylbenzene	1.3E+04		53
Total Xylenes	2.9E+05		1365

[a] These concentrations are representative of 10^{-6} carcinogenic risk.

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APPENDIX G
SITE-SPECIFIC TARGET CONCENTRATIONS FOR GROUNDWATER
REMEDIAL ACTION PLAN
RISK-BASED APPROACH TO REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Exposure Assumptions: Unlimited Land Use; Pathway Specific

INGESTION OF GROUNDWATER

VARIABLES IN CARCINOGENIC EQUATION

BW = body weight (kg)	70
ET = exposure time (hr/day) - site-specific	2
PC = dermal permeability constant (cm/hr)	chem-specific
benzene	2.10E-02

ALL OTHER VARIABLES AS DEFINED IN PREVIOUS SITE-SPECIFIC SSTL CALC. SHEET

VARIABLES IN NONCARCINOGENIC EQUATION

ALL OTHER VARIABLES AS DEFINED IN PREVIOUS SITE-SPECIFIC SSTL CALC. SHEET

Calculations

Carcinogenic Chemical Target Concentration Equation:

$C = (TR*BW*ATc*365)/(EF*ED*ET*(10^{-3})*4cm^3*PC*SF_o*SA)$

Noncarcinogenic Chemical Target Concentration Equation:

$C = (THQ * BW* ATn * 365d/yr)/(EF*ED*ET*(1/RFDo)*10^{-3}L/cm^3*PC*SA)$

Groundwater COC	SITE-SPECIFIC Noncarcinogenic Target Concentration	SITE-SPECIFIC Carcinogenic Target Concentration
Benzene	--	281 [a/]
Toluene	2.3E+05	
Ethylbenzene	1.2E+05	
Total Xylenes	2.3E+06	
Naphthalene	4.7E+04	

[a/] These concentrations are representative of 10^{-6} carcinogenic risk.

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BENZENE

CAS NUMBER

71-43-2

COMMON SYNONYMS

None.

ANALYTICAL CLASSIFICATION

Volatile organic.

PHYSICAL AND CHEMICAL DATA

Water Solubility: 1,791 mg/L [1]
Vapor Pressure: 95.19 mm Hg at 25°C [1]
Henry's Law Constant: 5.43×10^{-3} atm-m^3/mole (temperature not given) [1]
Specific Gravity: 0.879 at 15/5°C [2]
Organic Carbon Partition Coefficient: 31 - 143 [1]

FATE DATA: HALF-LIVES

Soil: 5 - 16 days [3]
Air: 2.09 - 20.9 days [3]
Surface Water: 5 - 16 days [3]
Groundwater: 10 days to 2 years [3]

NATURAL SOURCES

Crude oil, volcanoes, forest fires, plants [1].

ARTIFICIAL SOURCES

Gasoline, fuel oils, chemical industry, coke ovens, mining, manufacturing, cigarette smoke [1].

FATE AND TRANSPORT

Benzene will rapidly volatilize from surface soil and water. That which does not volatilize from permeable surface and subsurface soils will be highly to very highly mobile, and can be expected to leach to nearby groundwater which is not protected by a confining layer. It is fairly soluble, and will be carried with the groundwater to discharge points. It may be subject to biodegradation in soils, shallow groundwater, and surface water. Benzene will not be expected to significantly adsorb to sediment, bioconcentrate in aquatic organisms, or hydrolyze. Photodegradation may be a significant removal mechanism in surface waters which are not conducive to microbial degradation. Benzene will undergo significant photodegradation in air, but may be washed out with rain [1].

HUMAN TOXICITY

General. Benzene is absorbed into the body following ingestion, inhalation, and dermal contact, and must undergo metabolic transformation to exert its toxic effects. Metabolism occurs primarily in the liver, and to a lesser extent in the bone marrow [4]. The primary targets of benzene toxicity are the central nervous system and the blood [4,5]. Benzene is genotoxic to humans and the USEPA has placed it in weight-of-evidence cancer Group A, indicating that it is a human carcinogen [6].

Oral Exposure. A chronic oral RfD for benzene is currently under review by the USEPA [6]. Benzene is readily absorbed following oral exposure. The lowest reported fatal dose in humans is 50 mg/kg [5]. Acute oral LD_{50} values in animals include 930 to 5600 mg/kg in rats, 2000 mg/kg in dogs and 4700 mg/kg in mice [4,5]. Data regarding the ingestion of benzene in humans are limited to acute overexposure. Ingestion of 2 ml (29 mg/kg) has resulted in depression of the central nervous system, while ingestion of 10 ml (143 mg/kg) has been fatal [5]. The cause of death was usually respiratory arrest, central nervous system depression or cardiac collapse [4]. In animals, longer-term oral exposure has resulted in toxic effects on the blood (cytopenia: decrease in various cellular elements of the blood) and the immunological system (decreased white blood cells) [4]. There is no evidence that oral exposure to benzene causes effects on reproduction and development, but studies in animals suggest that benzene may affect fetal development [4]. There is no information regarding carcinogenic effects in humans following oral exposure to benzene, but studies in animals indicate that benzene ingestion causes cancer in various regions of the body [4]. An oral Slope Factor of 0.029 $(mg/kg/day)^{-1}$ is based on an increase in the incidence of leukemia in occupationally-exposed workers [6]. The oral Slope Factor was extrapolated from the inhalation data.

Inhalation Exposure. A chronic inhalation RfC for benzene is currently under review by the USEPA [6]. Benzene is readily absorbed following inhalation exposure. The lowest reported fatal concentration in humans is 6380 mg/m^3 for a 5 minute exposure [5]. Acute inhalation LC_{50} values in rats ranged from 10,000 ppm for 7 hours to 13,700 ppm for 4 hours [4,5]. Most of the available data regarding benzene exposure involve workers exposed in the workplace. The acute effects of benzene exposure involve the central nervous system. Brief exposure to concentrations of 700 to 3000 ppm can cause drowsiness, dizziness, headaches and unconsciousness, and exposure to concentrations of 10,000 to 20,000 ppm can result in death [4]. In most cases, the effects will end when exposure ceases. The hematopoietic system is the primary target of toxicity following long-term exposure: exposure for several months to years results in pancytopenia (reduction in red blood cells, platelets and white blood cells), while continued exposure for many years results in anemia or leukemia. The lowest concentration resulting in the hematological effects is approximately 10 to 50 ppm [5]. Benzene has been shown to cause chromosomal aberrations in bone marrow and lymphocytes in workers exposed to concentrations > 100 ppm [5]. Chromosomal damage has been found in animals at concentrations as low as 1 ppm [5]. Benzene is not known to be teratogenic (cause birth defects) in humans, but has been found to cause various problems in the developing fetus of animals (low birth weight, delayed bone formation) [4,5]. Occupational exposure to benzene has resulted in leukemia in exposed workers [4,5]. An inhalation Unit Risk of 8.3 x 10^{-6} $(ug/m^3)^{-1}$ is based on the incidence of leukemia in occupationally-exposed workers [6].

Dermal Exposure. Dermal exposure to benzene may cause redness and dermatitis [4,5]. Systemic effects have not been reported following dermal exposure to benzene.

REFERENCES

1. Howard, P.H., 1990. Handbook of Environmental Fate and Exposure Data For Organic Chemicals, Vol. II: Solvents. Lewis Publishers, Inc. Chelsea, Michigan. 546 pp.
2. Merck, 1989. The Merck Index. Eleventh Edition. Merck & Company, Inc. Rahway, NJ.
3. Howard, P.H., R.S. Boethling, W.F. Jarvis, W.M. Meylan, and E.M. Michalenko, 1991. Handbook of Environmental Degradation Rates. Lewis Publishers. Chelsea, Michigan.
4. ATSDR, 1991. Toxicological Profile for Benzene (Draft). Agency for Toxic Substances and Disease Registry. USPHS/USEPA. October 1991.
5. Arthur D. Little, Inc., 1989. The Installation Restoration Program Toxicology Guide. Volume 2. Cambridge, MA. July 1989.
6. USEPA, 1994. Integrated Risk Information System (IRIS). Data base. Online. February, 1994.

TOLUENE

CAS NUMBER

108-43-2

COMMON SYNONYMS

Methylbenzene.

ANALYTICAL CLASSIFICATION

Volatile organic.

PHYSICAL AND CHEMICAL DATA

Water Solubility: 534.8 mg/L at 25°C [1]
Vapor Pressure: 28.4 mm Hg at 25°C [1]
Henry's Law Constant: 5.94×10^{-3} atm-m^3/mole (temperature not given) [1]
Specific Gravity: 0.866 at 20/4°C [2]
Organic Carbon Partition Coefficient: 37 to 178 [1]

FATE DATA: HALF-LIVES

Soil: 4 to 22 days [3]
Air: 10 hours to 4.3 days [3]
Surface Water: 4 to 22 days [3]
Groundwater: 1 to 4 weeks [3]

NATURAL SOURCES

Volcanoes, forest fires, and crude oil [1].

ARTIFICIAL SOURCES

Gasoline, fuel oils, automobile exhaust, chemical industry, paints and lacquers [1].

FATE AND TRANSPORT

Much of the toluene released to surface soil will be lost to volatilization. It is mobile in soils and will leach to groundwater. Biodegradation occurs slowly in soil and groundwater, but is inhibited by high concentrations. Under ideal conditions of low concentration and acclimated microbial populations, rapid biodegradation may occur. Losses from surface water occur due to volatilization and biodegradation. It will not significantly adsorb to sediment or bioconcentrate in aquatic organisms. In the atmosphere it will degrade or be washed out with rain [1].

HUMAN TOXICITY

General. Toluene acts primarily on the central nervous system [4]. The USEPA has placed toluene in weight-of-evidence Group D; that is, it is not classifiable as to human carcinogenicity [5].

Oral Exposure. A chronic RfD of 0.2 mg/kg/day is based on a NOAEL of 223 mg/kg/day for changes in liver and kidney weights in a subchronic oral study in rats. The LOAEL in this study was a dose of 446 mg/kg/day [5]. Toluene is absorbed more slowly from the gastrointestinal tract than from the lungs [6]. The acute oral LD_{50} for adult rats is in the range of 5,000 to 7,300 mg/kg [4,6]. Brain damage was noted in mice receiving 1,250 mg/kg/day by gavage for 13 weeks [6].

Inhalation Exposure. The RfC of 0.4 mg/m^3 is based on a LOAEL of 88 ppm for central nervous system effects observed in humans following inhalation exposure [5]. Toluene is rapidly absorbed following inhalation by humans and animals [6]. The inhalation LC_{50} in mice is 5,300 ppm for an 8-hour exposure. Exposure of humans by inhalation to 200 ppm for 8 hours produced mild fatigue, weakness, confusion, lacrimation, and tingling of the skin. At 600 ppm, additional effects included euphoria, headache, dizziness, dilated pupils, convulsions, and nausea. After 8 hours at 800 ppm, symptoms were more pronounced; effects included nervousness, muscular fatigue, and insomnia persisting for several days. Exposure to concentrations of 10,000 to 30,000 ppm could lead to narcosis and death. Chronic abusive inhalation of toluene vapors by humans produces central nervous system impairment and emotional and intellectual disturbances. Uptake in the various brain regions is widespread due to the high lipid solubility of toluene and the high lipid content of the brain. Effects on animals following high levels of exposure include hearing loss, kidney effects, and lung lesions. High level oral intake by animals has resulted in weight increases in the liver and kidney, and brain tissue damage [4].

Dermal Exposure. The absorption of toluene through human skin is slow, falling within the range of 14 to 23 $mg/cm^2/hour$. Dermal contact with toluene by humans may cause skin damage. Application of toluene to the eyes of rabbits reportedly resulted in moderately severe injury [6].

REFERENCES

1. Howard, P.H., 1990. Handbook of Environmental Fate and Exposure Data For Organic Chemicals, Vol. II: Solvents. Lewis Publishers, Inc. Chelsea, Michigan. 546 pp.
2. Merck, 1989. The Merck Index. Eleventh Edition. Merck & Company, Inc. Rahway, NJ.
3. Howard, P.H., R.S. Boethling, W.F. Jarvis, W.M. Meylan, and E.M. Michalenko, 1991. Handbook of Environmental Degradation Rates. Lewis Publishers. Chelsea, Michigan.
4. Arthur D. Little, Inc., 1989. The Installation Restoration Program Toxicology Guide. Volume 2. Cambridge, MA. July 1989.
5. USEPA, 1994. Integrated Risk Information System (IRIS). On-line data base. February, 1993.

6. ATSDR, 1989. Toxicological Profile for Toluene. Agency for Toxic Substances and Disease Registry. USPHS/USEPA. December 1989.

ETHYLBENZENE

CAS NUMBER

100-41-4

COMMON SYNONYMS

None noted.

ANALYTICAL CLASSIFICATION

Volatile organic.

PHYSICAL AND CHEMICAL DATA

Water Solubility: 161 mg/l at 25°C [1]
Vapor Pressure: 9.53 mm Hg at 25°C [1]
Henry's Law Constant: 8.44 x 10^{-3} atm-m^3/mole [1]
Specific Gravity: 0.87 at 25/25°C [2]
Organic Carbon Partition Coefficient: 871 [1]

FATE DATA: HALF-LIVES

Soil: 3 to 10 days [3]
Air: 8.56 hours to 3.57 days [3]
Surface Water: 3 to 10 days [3]
Groundwater: 6 to 228 days [3]

NATURAL SOURCES

Coal tar and petroleum [4].

ARTIFICIAL SOURCES

Manufacture of styrene, solvent, petroleum refining, vaporization/spills of gasoline and diesel fuel, auto emissions, paints, inks, insecticides, and cigarette smoke [1,2,4].

FATE AND TRANSPORT

Ethylbenzene released to surface soils will probably undergo partial volatilization and, given its limited ability to sorb to soils (K_{oc} = 871), leach to groundwater. Evidence suggests that this material undergoes biodegradation in groundwaters, and may do so in soils if the initial loading doesn't prove toxic to soil-based microorganisms. If released to surface waters, ethylbenzene is expected to volatilize fairly readily. As with groundwaters, rapid biodegradation can be predicted after an initial acclimation period. Ethylbenzene shows only a slight to moderate tendency to adsorb to soils and sediments in waters. Bioconcentration in aquatic organisms is not expected to be significant (BCF for ethylbenzene = 145). Ethylbenzene is expected to exist in the atmosphere primarily as a vapor, based upon its vapor pressure value (9.53 mm Hg). Principally, ethylbenzene will be removed from the atmosphere via reaction with hydroxyl radicals; some washout via rainfall may be expected. [1]

HUMAN TOXICITY

General. Humans exposed to ethylbenzene may experience eye and throat irritation, decreased movement, and dizziness. Studies in animals have shown liver and kidney damage, nervous system changes, and blood changes [4]. The USEPA has placed ethylbenzene in weight-of-evidence group D, indicating that it is not classifiable as to human carcinogenicity [5].

Oral Exposure. A chronic RfD of 0.1 mg/kg/day is based on a NOEL of 97.1 mg/kg/day and a LOAEL of 291 mg/kg/day determined for liver and kidney toxicity in a rat subchronic to chronic oral bioassay [5]. Studies in animals revealed that ethylbenzene is quickly and effectively absorbed following oral exposure. The oral (gavage) LD_{50} in rats is reported to be 4,728 mg/kg. No information was located regarding death or health effects in humans following oral exposure [4].

Inhalation Exposure. The RfC of 1 mg/m^3 is based on a NOAEL of 434 mg/m^3 determined for developmental toxicity in rats and rabbits exposed via inhalation [5]. Ethylbenzene is rapidly and efficiently absorbed via inhalation in humans and animals. A 4-hour LC_{50} of 4,000 ppm was reported for rats. Exposure-related adverse effects in animals included those to liver and kidney, eye irritation, profuse lacrimation, CNS depression and ataxia. No deaths were reported for humans following inhalation of ethylbenzene. The effects observed in humans included pulmonary and ocular irritation, profuse lacrimation, chest constriction, dizziness, vertigo, and possible hematological alterations. Exposure of pregnant rats to levels above 138 ppm for 24 hours/day for 9 days had adverse developmental effects [4].

Dermal Exposure. Liquid ethylbenzene is rapidly absorbed through the skin; however, absorption of vapors through the skin is minimal. The dermal LD_{50} in rabbits for liquid ethylbenzene was reportedly 15,415 mg/kg. Ethylbenzene appears to be a slight eye irritant in rabbits [4].

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XYLENES

CAS NUMBER

1330-20-7

COMMON SYNONYMS

Xylene.

Note: There are three isomers (forms) of xylene: ortho, meta, and para, also known as 1,2-, 1,3-, and 1,4-xylene, respectively.

ANALYTICAL CLASSIFICATION

Volatile organic.

PHYSICAL AND CHEMICAL DATA

Water Solubility: 146 - 175 mg/L at 25°C [1]
Vapor Pressure: 6.6 - 8.7 mm Hg at 25°C [1]
Henry's Law Constant: 5.1×10^{-3} to 7.7×10^{-3} atm-m^3/mole at 25°C [2]
Specific Gravity: 0.880 at 20/4°C (*o*-xylene) [3]
Organic Carbon Partition Coefficient: 25.4 - 204 [1]

FATE DATA: HALF-LIVES

Soil: 1 - 4 weeks [4]
Air: 2.6 hours - 1.8 days [4]
Surface Water: 1 - 4 weeks [4]
Groundwater: 2 weeks - 1 year [4]

NATURAL SOURCES

All three isomers of xylene occur in petroleum. 1,2-Xylene is found additionally in coal tar, forest fire products, and plants [1].

ARTIFICIAL SOURCES

Gasoline, fuel oils, and their combustion products. Petroleum refining, chemical industry; aerosols of paints, varnishes, and shellacs. Wood-burning stoves and fireplaces [1].

FATE AND TRANSPORT

Xylenes are moderately mobile in soil and may leach to groundwater where they are known to persist for several years despite evidence of biodegradation in both soil and groundwater. The dominant removal process in surface water is volatilization, but this is not a rapid process. Some adsorption to sediment will occur. Once released to the atmosphere, xylenes will undergo photochemical degradation at a moderate rate [1].

HUMAN TOXICITY

General. The primary target of xylenes toxicity is the central nervous system [2,5]. Xylenes are considered to be nongenotoxic. The USEPA has placed xylenes in weight-of-evidence cancer Group D, indicating that they are not classifiable as to human carcinogenicity [6].

Oral Exposure. A chronic oral RfD of 2 mg/kg/day is based on a NOAEL of 250 mg/kg/day for hyperactivity, decreased body weight and increased male mortality in a chronic study in rats [6]. Acute oral LD_{50} values for xylenes ranged from 3523 to 8600 mg/kg in rats and 5251 to 5627 mg/kg in mice [2,5]. Death in humans has been reported following the ingestion of xylenes, but the fatal dose is not known [2]. Reports of the ingestion of xylenes in humans are generally lacking. In animals, oral exposure to xylenes results in effects on the liver (increased liver enzymes and weight), the kidenys (increased kidney weight), and the nervous system (impairment of visual function, hyperactivity) [4]. Information is not available regarding the effects of ingested xylene on reproduction or development in humans, and the results of developmental studies in animals are inconclusive [2]. There is no conclusive evidence that oral exposure to xylenes causes cancer in humans or animals, therefore, an oral slope factor is not available [6].

Inhalation Exposure. An inhalation RfC for mixed xylenes is considered non-verifiable by the USEPA [7]. Xylenes are readily absorbed following inhalation exposure. Acute inhalation LC_{50} values of 6350 to 6700 ppm (4-hour exposure) were reported in rats for mixed xylenes [2]. LC_{50} values for the separate isomers are comparable to the mixture. Cause of death was usually respiratory failure and/or sudden ventricular fibrillation. In humans, inhalation of approximately 10,000 ppm xylenes has been fatal [2]. Exposure of humans to 90 ppm xylene has produced impairment of reaction time, manual coordination and body balance [5]. Brief exposure to concentrations of 200 ppm has caused irritation of the eyes, nose and throat. and exposure to concentrations above 200 ppm has resulted in nausea, vomiting, abdominal pain and loss of appetite [5]. Long-term high-level occupational exposure to xylenes (> 200 ppm) has resulted in central nervous system effects, incoordination, nausea, vomiting, and abdominal pain [5]. Studies in laboratory animals suggest that xylenes have a relatively low chronic toxicity. Some data in animals suggest possible kidney and liver impairment with high level inhalation exposures (>1000 ppm) [5]. Information regarding the effects of xylenes on human reproduction and development are not available, but teratogenicity, fetotoxicity, and maternal toxicity have been observed in animals [2,5]. Xylenes have been found to cross the human placenta, therefore, there is sufficient reason for concern for pregnant women who are exposed to xylenes [2,5]. It is not known whether inhaled xylenes cause cancer in humans or animals, therefore, an inhalation unit risk is not available [6].

Dermal Exposure. Acute dermal LD_{50} values in rabbits of 14.1 ml/kg and greater than 5.0 ml/kg are reported for m-xylene and mixed xylenes, respectively [5]. Xylene is a skin irritant and causes redness, defatting and dryness. Vesicles may form following prolonged skin contact [2,5].

ECOLOGICAL TOXICITY

General. Xylenes are not a priority pollutant because they have low acute and chronic toxicity. Xylenes move through the soil/groundwater system when present at low concentrations, dissolved in water and adsorbed on soil, or as a separate organic phase resulting from a spill of significant quantities. Xylenes readily volatilize from water, are moderately adsorbed on soil, and have a moderate potential for bioaccumulation [8]. No information on biomagnification of xylenes was available in the technical literature.

Vegetation. Nearly all xylenes (98.8 percent) are expected to be sorbed into the soil. For the portion of xylenes in the gaseous phase of soil (0.5 percent), diffusion through the soil/air pores up to the ground surface and removal by wind will be a significant loss pathway [8]. Review of the technical literature did not produce information regarding the phytotoxic effects of xylenes.

Aquatic Life. The half-life of xylenes in surface water has been calculated as 2.6 to 11.2 days [9]. Under normal environmental conditions, xylenes are not expected to undergo hydrolysis because they contain no hydrolyzable functional groups [8]. The LC_{50} value for freshwater fish was approximately 30 mg/L [9]. The 96-hour LC_{50} values for fathead minnows were 26.7 mg/L in soft water and 28.8 mg/L in hard water [10]. The 96-hour LC_{50} for bluegills was 20.9 mg/L in soft water [10]. There are no federal or state water quality standards established to protect aquatic life [11].

Wildlife. Xylenes are considered to be of low acute and chronic toxicity to birds and mammals [12]. No changes were found in rats, guinea pigs, dogs, and monkeys continuously exposed to 80 ppm for 127 days, nor in rats exposed to 700 ppm for 130 days [8]. Japanese quail showed no signs of toxicity at oral concentrations of 5,000 to 20,000 ppm (approximately 600 to 2,400 mg/kg body weight) [9]. Mallard eggs were immersed in xylene (10%) for 30 seconds and no significant effects on embryonic weight and length were observed when compared to controls [13]. Arthur D. Little, Inc. [8] reported an oral LD_{50} for rats at 4,300 mg/kg.

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NAPHTHALENE
2-METHYLNAPHTHALENE

GENERAL

There is relatively little information available on 2-methylnaphthalene as compared to naphthalene. Therefore, all information below refers to naphthalene unless explicitly stated otherwise.

CAS NUMBERS

Naphthalene:	91-20-3
2-Methylnaphthalene:	91-57-6

COMMON SYNONYMS

Naphthalene: Naphthene, Tar Camphor.
2-Methylnaphthalene: Beta-methylnaphthalene

ANALYTICAL CLASSIFICATION

Semi-Volatile Organic.

PHYSICAL AND CHEMICAL DATA

	Naphthalene	2-Methylnaphthalene
Water Solubility (mg/L at 20°C) [1]	31.7	ND
Vapor Pressure (mm Hg at 25°C) [1]	0.087	ND
Henry's Law Constant (atm-m^3/mole) [1]	4.6×10^{-4}	ND
Specific Gravity (20/4°C) [1]	1.145	1.0058
Organic Carbon Partition Coefficient [1]	933	ND

FATE DATA: HALF-LIVES

Soil: 16.6 to 48 days [2]
Air: 2.96 to 29.6 hours [2]
Surface Water: 12 hours to 20 days [2]
Groundwater: 1 to 288 days [2]

NATURAL SOURCES

Crude oil; natural, uncontrolled combustion (i.e., forest fires) [3,4].

ARTIFICIAL SOURCES

Naphthalene: Petroleum refining, mothball use and manufacture, coal tar distillation, pitch fumes, chemical intermediate (i.e., phthalic anhydride manufacture), vehicle emissions, combustion processes (i.e., refuse combustion), tobacco smoke, and oil spillage [3,4].

2-Methylnaphthalene: Synthesis of organic compounds such as insecticides, and release from gasoline due to its use as an additive [1,5].

FATE AND TRANSPORT

Naphthalene's sorption to soil ranges from low to moderate, depending upon the organic carbon content of the soil, and will leach rapidly through sandy soils. Volatilization from the uppermost soil layer will be important, but will lessen in importance with soil depth. In addition, volatilization from moisture-saturated soil is not expected to be important. Biodegradation is expected to be rapid in soils previously contacted with other polycyclic aromatic hydrocarbons (PAHs), but slow in "virgin" soils [3].

Volatilization, photolysis, sorption (to suspended solids, sediments, etc.), and biodegradation are the primary removal mechanisms for naphthalene in waters. The actual predominant mechanisms change with variations in several factors (i.e., water flow rate, level of sediments/suspended soils, water clarity, etc.) In addition, biodegradation rates of naphthalene in water vary with changes in concentration of naphthalene (higher concentrations yield higher rates), "virgin" versus oil-polluted water (quicker in oil-polluted waters), actual pollution site (more rapid biodegradation in sediments than waters), aerobic versus anaerobic conditions (no biodegradation in anaerobic conditions), and so on. Bioconcentration in aquatic organisms is expected to be moderate, except for accelerated bioconcentration in organisms lacking an aryl hydroxylase enzyme system (i.e. phytoplankton, snails, mussels). Naphthalene in the atmosphere reacts during daylight hours with hydroxyl radicals, and during nighttime hours with nitrate radicals. Photolysis is also expected in the atmosphere [3].

HUMAN TOXICITY

General. The breakdown of red blood cells is the primary health concern for humans exposed to naphthalene. Human deaths following ingestion have occurred [1]. The USEPA has placed naphthalene in weight-of-evidence Group D, indicating that it is not classifiable as to human carcinogenicity [6]. The USEPA does not currently provide any toxicity values for 2-methylnaphthalene [6,7].

Oral Exposure. Both the chronic and subchronic RfDs for naphthalene of 0.04 mg/kg/day are based on a NOEL of 50 mg/kg/day for decreased body weight observed in a subchronic oral (gavage) study in rats [7]. Clinical evidence indicates that naphthalene is absorbed by humans in significant quantities via the oral route. The oral LD_{50} reported for naphthalene in rats ranges from 2,200 to 2,400 mg/kg in rats [1]. The oral LD_{50} reported for 2-methylnaphthalene in rats is 1,630 mg/kg [5]. Lethal doses of naphthalene in humans have ranged from as low as 74 mg/kg to as high as 574 mg/kg [1]. Ocular damage has been documented in humans and animals following oral exposure [1]. Symptoms of intoxication include: nausea, vomiting, headache, diaphoresis, hematuria, hemolytic anemia, fever, central nervous system depression, hepatic necrosis, jaundice, convulsions, and coma [1,2,8]. Administration of 300 mg/kg/day to pregnant mice resulted in a decrease in the number of live pups per litter [1].

Inhalation Exposure. An inhalation RfC was not reported for naphthalene [6,7]. Clinical reports suggest that inhaled naphthalene may be absorbed in sufficient quantity to produce adverse health effects in humans; however, no quantitative absorption data were located for humans or animals. One study, on rats, reported a NOAEL of 78 ppm for a 4-hour exposure. Symptoms and effects of inhalation exposure in humans include: headache, nausea, vomiting, abdominal pain, malaise, confusion, anemia, jaundice, and renal disease. No information was found regarding developmental and reproductive effects [1].

Dermal Exposure. Limited evidence in human infants indicated that hemolytic anemia may have resulted from dermal exposure to an unknown quantity of naphthalene. A NOAEL of 2,500 mg/kg was reported for rats. Naphthalene is a mild dermal and ocular irritant [1].

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APPENDIX H

SCREENING AND DEVELOPMENT OF REMEDIAL ALTERNATIVES

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SCREENING AND DEVELOPMENT OF REMEDIAL ALTERNATIVES

1.1 OVERVIEW

This appendix identifies a variety of remedial approaches and technologies that were considered in developing remedial alternatives for Area D. This initial screening was based on three primary evaluation criteria: effectiveness in meeting SDDENR criteria for inactive status, technical and administrative implementability, and relative cost. The purpose of this screening was to quickly focus the remedial action plan on the most promising and cost-effective methods for remediating Area D. This appendix focuses on how selected active remedial technologies could be combined with intrinsic remediation to achieve an effective site cleanup.

2.1 SCREENING OF REMEDIAL TECHNOLOGIES

Table 1 provides a summary of the remedial approaches and technologies considered for Area D. All of these technologies are appropriate for the remediation of fuel-contaminated soils or groundwater. Technologies which are used for non-fuel contaminants have been purposely deleted from this focused initial screening. Several of the most promising technologies considered during screening have been retained as candidates for the development of remedial alternatives and evaluated in Section 8 of the RAP. The following paragraphs provide a brief description of each approach or technology group and its site-specific applicability for this site.

2.1.1 Long-Term Soil, Soil Gas, and Groundwater Monitoring

Long-term monitoring of soils and groundwater is essential in evaluating the progress of intrinsic and engineered remediation and for ensuring that cleanup criteria are achieved over a specified time interval.

2.1.1.1 Soil and Soil Gas Monitoring

Soil and soil gas monitoring provides information for assessing the effectiveness of an implemented soil remedial technology. Extensive soil sampling at the Area D has revealed moderate contamination in unsaturated soils in the source area and in saturated soils outside of the source area. All detected soil contaminants are below target risk-based remedial goals that are protective of human health and the environment given current and future proposed land uses. Soil gas is used as an indicator of VOC reduction, and oxygen and carbon dioxide concentrations can indicate the level of hydrocarbon biodegradation occurring in the soil. Long-term soil gas monitoring was retained for further evaluation.

2.1.1.2 Groundwater Monitoring

Groundwater monitoring is essential for evaluating the effectiveness of implemented groundwater remediation technologies, particularly natural attenuation processes. Sentry or model verification wells can be utilized to monitor COCs and their attenuation within and near the existing plume. The predictions of fate and transport models are often verified using sentry wells within the plume. POA wells can be established at downgradient locations to ensure that contaminants do not advance at concentrations that may present an unacceptable risk beyond an area under reliable exposure controls. Sufficient sentry wells are now available at this site to assess both vertical and horizontal contaminant transport and attenuation. The suitability of existing wells for POA monitoring is addressed in Section 10 of the RAP, the Long-Term Monitoring Plan. Long-term groundwater monitoring was retained as a key component of the remedial alternatives for this site.

2.1.2 Land and Groundwater Use Control

Some degree of land and groundwater use control will be required if contaminant concentrations in groundwater at Area D are going to exceed state promulgated groundwater quality standards under SDDENR inactive status. Land and groundwater use controls can be enacted to minimize the potential for direct receptor contact with site contamination.

2.1.2.1 Land Use Control

Physical barriers and deed restriction/easements can be used to control land use. Access to this site is currently limited by fencing around the base perimeter and around the site itself. Physical barriers and deed restrictions on land and resource uses were retained for further evaluation.

2.1.2.2 Groundwater Use Control

Groundwater use controls can eliminate the possibility of direct exposure of site workers to contaminated groundwater. Groundwater use can be controlled by regulating well permits, minimizing excavations below the water table, and when no other source of drinking water is available, installing point-of-use treatment systems. Contaminated groundwater at this site remains within an area under base control, and no active drinking water wells exist on or near the site. The regulation of future well permits in the vicinity of Area D was retained for further evaluation.

2.1.3 Public Education

At many hazardous waste sites, public education is required to inform the public of the risks associated with site contamination and to provide the necessary warnings to prevent unintentional contact with site soils or groundwater. Although no human health risk is currently associated with this site, any future release of this property to private citizens or business should be accompanied with a clear understanding of where jet fuel contamination may still exist and the appropriate land uses that will prevent exposure. As required by SDDENR guidance for attainment of inactive status, public education was retained as a remedial approach.

2.1.4 Containment of the Groundwater Plume

Plume containment uses either hydraulic controls, such as limited groundwater pumping, or physical barriers such as slurry walls, to minimize downgradient plume migration. This strategy is most often used to halt the advance of highly contaminated groundwater before it impacts downgradient drinking waters or surface waters.

2.1.4.1 Hydraulic Controls

Hydraulic controls extract contaminated groundwater to prevent further migration of the plume. Hydraulic controls considered for this site include a groundwater interceptor trench and downgradient extraction wells. Hydrogeology at the site is very discontinuous, as discussed in Section 3 of the RAP. Areas yielding large amounts of groundwater are isolated, thus groundwater pumping may be ineffective in controlling the flow of groundwater at Area D. Therefore, groundwater pumping to control the flow of contaminants at Area D was not retained as a remedial alternative.

A groundwater interceptor trench or french drain could be placed downgradient of Area D to intercept all groundwater leaving the source area at the site. The trench would be installed to competent bedrock and thus intercept any bedrock channels that may be causing preferential groundwater flow. Depth to bedrock along the downgradient edge of Area D is approximately 25 feet bgs, a feasible depth for excavation and installation of an interceptor trench. After collection in the drain, contaminated groundwater would be pumped to the surface and treated by air stripping and discharged to the sanitary sewer. A detailed discussion on aboveground treatment of groundwater can be found in Section 2.1.6 of this appendix. Since groundwater extraction could provide a conservative margin of protection against plume migration and possibly remediate the plume more rapidly than intrinsic remediation alone, it was retained as a remedial alternative.

2.1.4.2 Physical Groundwater Barriers

Slurry walls, grout curtains, and sheet pilings are physical structures capable of limiting downgradient contaminant migration. However, contaminants are not removed by such physical barriers, they are only contained. When compared to an interceptor trench where contaminants are contained and removed, containment alone is a less effective option. Physical groundwater barriers were not retained for further consideration.

2.1.4.3 Reactive/Semipermeable Barriers

Reactive, semipermeable barriers are an emerging technology which uses a downgradient chemically reactive wall or biologically active treatment zone to intercept and treat groundwater contaminants as they pass through the treatment zone. This technology has the advantage over simple physical barriers in that contaminants are actually destroyed and groundwater flow is uninterrupted. Installation of a barrier wall may be possible at Area D, however, the long-term maintenance cost would be very large when compared to the cost of the interceptor trench already considered in this RAP. Reactive walls and biological active zones were not retained for further evaluation.

2.1.5 *In situ* Groundwater Treatment

In situ treatment includes both engineered and natural processes which are capable of destroying or immobilizing dissolved contamination in place. *In situ* treatment is generally less expensive than aboveground treatment because there is no need to extract, treat, and then dispose of groundwater.

2.1.5.1 Intrinsic Remediation

As thoroughly discussed in Section 6 of the RAP, intrinsic remediation takes advantage of destructive and nondestructive attenuation mechanisms to bring about a net reduction in groundwater contaminant concentrations. Destructive attenuation mechanisms include biodegradation, abiotic oxidation, and hydrolysis. Nondestructive attenuation mechanisms include sorption, dilution, and volatilization (Wiedemeier *et al.*, 1994). At this site, the decrease in dissolved contamination with increasing distance from the source and geochemical evidence both confirm that intrinsic remediation is a fairly significant and ongoing cleanup process at this site. Therefore, this remedial approach was retained from the screening process.

2.1.5.2 Enhanced/Active Biological Groundwater Treatment via Biosparging

Enhanced *in situ* biodegradation takes advantage of natural biological processes by providing enhanced electron acceptor conditions and, when required, enhanced nitrogen/phosphorus (i.e., nutrient) conditions to stimulate microbial growth and more rapid biodegradation. Section 6 of the RAP provides geochemical evidence that a low oxygen concentrations in groundwater at Area D may be limiting the biodegradation of dissolved contaminants in the plume. Low flow-rate air injection into groundwater, known as biosparging, can be used to increase dissolved oxygen concentrations in groundwater and promote biodegradation. As discussed in Section 7, a biosparging pilot test at Area D was aborted when variable subsurface conditions were discovered at the site. A borehole drilled for the installation of a biosparging point in the source area produced no groundwater. As a result of these site conditions, biosparging was not retained for evaluation as a method of enhancing natural biodegradation in the source area.

2.1.6 Aboveground Groundwater Treatment

Groundwater extraction and aboveground groundwater treatment offers the flexibility of more engineering controls than *in situ* remediation, and can usually treat a wider range of contaminants than *in situ* treatment. Groundwater extraction also provides greater control over plume migration and can be focused in areas of greatest contamination. As discussed in Section 2.1.4.1 of this appendix, a groundwater interceptor trench has been retained for further evaluation. Treatment technologies most appropriate for removing dissolved hydrocarbons from extracted groundwater include bioreactors, air stripping methods, and activated carbon adsorption. Treatment facility construction, operation, maintenance, and monitoring will require greater financial resources. Pump installations and maintenance also add to the cost of this technology group.

2.1.6.1 Groundwater Extraction

Groundwater extraction has been a standard approach used to remediate many fuel-contaminated aquifers. This technology has been most successful in sand and gravel aquifers with low natural organic carbon content. Under these conditions organic contaminants are less likely to sorb to soil particles and are more likely to remain dissolved and available for extraction. These favorable aquifer conditions generally exist in the gravel overlying the weathered Pierre Shale at Area D. As mentioned in Section 2.1.4.1, because groundwater extraction and treatment could provide a conservative margin of protection against plume migration and possibly remediate the plume more rapidly than intrinsic remediation, it was retained for consideration in alternative development.

2.1.6.2 Bioreactors

Bioreactors typically provide an enhanced environment where biodegradation rates are higher than those observed *in situ*. The *ex situ* nature of the bioreactor allows for greater control of reactor conditions (e.g., temperature, pH, mixing) and some optimization of degradation pathways. The hydraulic loading of bioreactors is often limited because complete biodegradation requires long retention times to degrade low concentrations of hydrocarbons. In the case of slower degrading PAH compounds, the contaminants must first be sorbed to filter media and retained to complete the biodegradation process. In the climate of South Dakota, bioreactors would require heating during winter months to maintain high degradation rates. Due the high maintenance requirements, and additional costs of operating a bioreactor, this technology was not eliminated from further consideration.

2.1.6.3 Air Stripping

Air stripping technologies contact contaminated groundwater with clean air to volatilize (strip) dissolve contaminants from the aqueous phase. Air stripping is most effective for compounds with Henry's Law constants greater than 0.001 including benzene, toluene, ethlybenzene, and xylenes, which have Henry's Law constants of 0.0054, 0.0066, 0.0079, and 0.0049-0.007, respectively. The highest total BTEX concentration measured in the source area during the 1994 risk-based field investigation October of 1994 was just over 5.4 mg/L at well MW-6. The average total BTEX concentration measured in the three most contaminated wells in the source area was approximately 4.8 mg/L. For long-term operation, air stripping would be the most effective and cost efficient *ex situ* groundwater treatment technology. Therefore, air stripping was retained as a treatment process option.

2.1.6.4 Activated Carbon

Activated carbon is a commonly used method of removing BTEX contaminants from groundwater as it passes through a packed-bed canister of granular activated carbon (GAC). To remediate groundwater using GAC, the carbon would have to be replaced or recharged on a regular basis. This replacement would be very expensive and thus cost prohibitive. Activated carbon treatment was not retained as a possible aboveground treatment technology in the event that groundwater extraction is selected as a site remedy.

2.1.6.5 Direct Discharge to Sanitary Sewer

Direct discharge of extracted, contaminated groundwater to an industrial wastewater treatment plant (IWWTP) is an alternative for treatment if a treatment plant is available and can accept fuel-tainted waters. The Base treatment plant will not accept untreated water, and a public IWWTP sewer connection does not exist in the vicinity of the Area D. Trucking of extracted groundwater to a private treatment works is infeasible, due to the large transportation costs. Direct discharge to a IWWTP was not retained for further evaluation.

2.1.7 Treated Groundwater Discharge/Disposal

The extraction and treatment of contaminated groundwater will require a method of disposal for treated water which meets all appropriate discharge standards of the State of South Dakota and EPA. Several methods of onsite and offsite disposal were identified for this initial screening.

2.1.7.1 Discharge to a Sanitary Sewer

A sanitary sewer line does exist near this site. According to Base utility maps, a sewer line runs approximately north/south across the field to the east of Area D. After treatment, groundwater could be discharged into this line. Cost for this alternative would be minimal and it could be easily implemented. Discharge to a sanitary sewer was retained as a potential disposal method for treated groundwater.

2.1.7.2 Reinjection to Groundwater

Reinjection of treated groundwater into the subsurface can be accomplished through several methods. Surface application using a sprinkler system would be possible during summer months but freezing conditions would make it impractical during the winter. Reinjection wells have been used to return treated groundwater to the subsurface; however, injection wells require frequent maintenance to reduce the impacts of plugging, which almost always occurs over time. Since disposal to the sanitary sewer would be more practical and cost effective at Area D, reinjection trenches have not been retained as a possible option for the discharge of treated groundwater.

2.1.7.3 Discharge to Surface Drainage

Under this option, treated groundwater would be discharged into the local stormwater drainage which eventually discharges into Box Elder Creek south of the Base. Storm drainage at the site consists of a storm water drain located just to the west of Building 8215. An underground concrete conduit drains storm water to the south. A discharge permit and frequent monitoring would be required to ensure protection of potentially sensitive downstream surface waters and compliance with federal and SDDENR regulations. Due to the problems with discharge permitting and the difficulty of routing water to the storm water drain, this option was not retained for further evaluation.

2.1.8 Source Removal/Soil Remediation Technologies

The removal or reduction of concentrated contaminants in the source area is normally an important element of a comprehensive site remediation. Two primary sources of contamination can potentially exist at fuel contaminated sites: free-phase product (LNAPL) and residual fuels which are sorbed or occluded within the soil matrix. Both types of sources are present at Area D.

During the 1994 field investigation, a thin layer of LNAPL was present in MW-6. This groundwater monitoring well was the only sampling location at Area D containing LNAPL at the time of the investigation. It appears that the LNAPL at Area D is isolated and discontinuous. However, recoverable LNAPL at the site must be removed in order to be considered by the SDDENR for inactive status. As a result, LNAPL removal technologies will be considered as a part of this technology screening process.

Residual fuel contamination at this site appears to be spread throughout the entire soil profile in the source area (MW-6, MW-39, and MW-40) and limited to a thin layer of soil in the capillary fringe and saturated soils downgradient of the source area. This contamination was typically encountered in the coarse gravel 1 to 2 feet above the top of weathered bedrock. Depth and thickness of contamination varied with lithology across the site. Analysis of soil samples indicate that remaining BTEX contamination is below risk-based cleanup criteria that are protective of human health and the environment. SDDENR has not promulgated cleanup standards for BTEX compounds in soil. However, soil leaching modeling results (Section 6.6) indicate that contaminated unsaturated soils may be a source of groundwater contamination at Area D. Soil remediation techniques also are discussed because contaminated soils must be remediated "to the maximum extent possible" under SDDENR guidelines for attainment of inactive status. Common soil remediation technologies such as soil vapor extraction and *in situ* bioventing, which depend on soil gas movement, will be effective due to the highly permeable nature of the coarse gravel found in the subsurface at Area D. Soil flushing using surfactants is another option for reducing fuel residuals that is evaluated in this section.

2.1.8.1 Bioslurping

Bioslurping was evaluated as a practical method for the removal of isolated areas of LNAPL at Area D. Bioslurping is a vacuum-mediated free product recovery and bioremediation technique that is applicable for the remediation and removal of measurable layers of LNAPL on groundwater. Vacuum enhanced product recovery improves the rate of recovery and decrease total treatment time. To determine the feasibility of implementing bioslurping at Area D, a LNAPL baildown and recovery test was performed at MW-6 in October 1995. Test results indicate very slow rates of product recovery in the well. Slow recovery times typically indicate that active recovery techniques will not significantly increase long-term product recovery rates when compared to passive techniques such as skimming or wicking. Bioslurping for the removal of isolated LNAPL at Area D was not retained for further evaluation.

2.1.8.2 Product Skimmer Pumps and Wicks

Skimmer pumps and wicks were evaluated for LNAPL removal at Area D. Both recovery techniques are suitable for recovering product in areas where the LNAPL layer is thin (<1 foot). Skimmer pumps only operate after being activated by a float switch which floats on the surface of the LNAPL. The recovery well only pumps product after the LNAPL layer reaches a preset thickness and the float switch is tripped. Wicks are a passive product recovery technique. Hydrophobic wicks are placed into recovery wells and left in place for a period of time. During this time, hydrocarbons are sorbed onto the surface of the wick and removed from the groundwater surface. Once the wicks become saturated with product they are removed from the well, recharged and/or replaced.

Both technologies are suitable for application at Area D and could be placed in existing wells. Cost for wicks would be substantially lower than skimmer pumps which would require electrical connections and product recovery piping. Since MW-6, the only well at the site containing LNAPL, is in the center of an active concrete driveway, making electrical and pneumatic connections would be costly and difficult. A wick could be placed in the well without requiring any connections or surface disturbances. Passive wicking was retained for further evaluation.

2.1.8.3 Soil Vapor Extraction

Soil vapor extraction mechanically withdraws soil gas from the vadose zone to the surface using vent wells. If necessary, offgas can be treated prior to discharge into the atmosphere, although treatment can easily double the cost of this technology. By extracting soil gas from the vadose zone, the desorption of VOCs from soils into soil gas is enhanced. Soil vapor extraction is very effective in highly permeable soil such as the coarse gravels present in deeper soils at this site. Because soil vapor extraction also results in an influx of oxygenated soil gas from clean soils, it also enhances the biodegradation of less volatile hydrocarbons. Soil vapor extraction was not retained for further evaluation because bioventing would provide the same benefits without the transfer of VOCs to the atmosphere.

2.1.8.4 Bioventing

Bioventing is mechanically similar to soil vapor extraction except that this technology uses much lower rates of air injection to provide the necessary oxygen to sustain biological degradation, and does not create an undesirable discharge of VOCs into the atmosphere. Bioventing rates of air injection are typically one-tenth of vapor extraction rates for the same site. The effectiveness of this technology has been demonstrated in a major pilot testing program conducted at over 140 Air Force sites, including over 50 sites contaminated with JP-4 jet fuel (Downey, 1994). A bioventing pilot test conducted at Area D is described in Section 7 of the RAP. Bioventing proved to be effective in removing BTEX from vadose zone soils at Area D and was retained for further evaluation.

2.1.8.5 Surfactant Soils Washing

Soil washing is used to enhance the natural partitioning of contaminants from the soil into the groundwater, and is generally associated with a groundwater extraction system. The more strongly sorbed compounds may require surfactant soil washing to facilitate the dissolution process. *In situ* soil washing is only effective in more permeable aquifer materials, such as those at Area D. Soil washing usually involves the addition of a surfactant compound that has a nonpolar "tail" to dissolve the contaminant, and a polar end so that the formed miscelle is soluble in water. Biodegradable surfactants are desirable to ensure that new recalcitrant chemicals are not introduced into the aquifer.

Two significant disadvantages are associated with this technology. Because surfactants are added in relatively high concentrations, they will exert a significant biological oxygen demand on the aquifer. This additional organic loading may exceed the natural assimilative capacity of the aquifer and promote the migration of both surfactant and fuel hydrocarbons. The second problem is that when the surfactant solution is recovered, it is difficult to separate contaminants from the surfactants so that surfactants can be recycled. Treatment of surfactant-laden groundwater can be achieved with activated carbon, but the surfactant will rapidly load the carbon, resulting in unacceptable treatment costs. Due to these technical difficulties, surfactant soils washing was not retained for further evaluation.

2.1.9 Soil Excavation and Treatment

Excavation and surface treatment of contaminated site soils is not appropriate at this site given the existence of buildings, roads, and pipelines in the source area. Excavation and aboveground treatment options such as biological treatment or thermal treatment were not retained for further evaluation.

3.1 SUMMARY OF RETAINED REMEDIAL TECHNOLOGIES

Based on the initial technology screening discussed in Section 2 of this appendix and summarized in Table 1, several remedial approaches and technologies have been retained for the development of remedial alternatives and more detailed analysis. These technologies were selected to provide a range of passive to more active response actions, all of which can attain eligibility for SDDENR inactive status and maintain contaminant concentrations that are protective of human health and the environment in the industrial setting. While attaining these goals, all of the presented alternatives will eventually remediate the site to state promulgated groundwater quality standards, though in different time frames and at different costs. The following remedial approaches and technologies have been retained :

- Long-term soil gas and groundwater monitoring;
- Limited land use controls;
- Groundwater use controls;
- Public education;

TABLE 1
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR SOIL AND GROUND WATER REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

General Response Action	Technology Type	Process Option	Technical Implementability	Effectiveness in Attaining Target Remedial Goals	Relative Cost	Retain
Long-Term Monitoring	Periodic Groundwater Monitoring	Sentry Wells	Many existing wells are available to confirm the progress of remediation.	Necessary component of all remediation strategies	Low	Yes
		Point-of-Compliance Wells	Sufficient distance exists between the plume and point-of-compliance to locate several additional wells.	Necessary component of all remediation strategies	Low	Yes
	Periodic Soil/Soil Gas Monitoring	Installation of Additional Soil Borings	Extensive soil sampling indicates little soil contamination above screening criteria. Soil gas monitoring useful for checking bioremediation.	Additional soil sampling necessary in future to document decrease in benzene concentrations.	Low	Yes
Institutional Controls	Land and Ground Water Use Control	Land Use Control/Regulate Well Permits	Plume area is currently within the Base boundary. Land-use and ground water use are under Base jurisdiction.	Necessary component of risk-based cleanup	Low	Yes
		Seal/Abandon Existing Wells	No drinking water wells located within 1,000 feet of plume.	Not required at this site	Low	No
		Point-of-Use Treatment	No groundwater is extracted from the plume area for use. Other sources of drinking water are available at the site.	Poor	Moderate	No
	Public Education	Meetings/ Newsletters	Important to convey a clear understanding of acceptable land and groundwater use.	Necessary to obtain SDDENR inactive status	Low	Yes
Containment of Plume	Hydraulic Controls	Interceptor Trench Collection	Thin saturated zone and shallow bedrock facilitate construction. Technique will intercept all bedrock channels and assure contaminant removal.	High	High	Yes

TABLE 1 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR SOIL AND GROUND WATER REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

General Response Action	Technology Type	Process Option	Technical Implementability	Effectiveness in Attaining Target Remedial Goals	Relative Cost	Retain
Containment of Plume (cont.)	Hydraulic Controls (cont.)	Minimum Pumping/Gradient Control	A line or semicircle of vertical pumping wells could be located along the leading edge of plume to intercept and halt the advance of the plume. Nonhomogereous hydrogeology would decrease effeciency.	Low	High	No
	Physical Controls	Slurry Walls/Grout Curtains	Requires significant disruption. Limited effectiveness.	Moderate	High	No
		Sheet Piling	Requires significant disruption. Limited effectiveness.	Moderate	High	No
	Reactive/Semi-Permeable Barriers	Biologically Active Zones	Natural biodegradation of BTEX/PAH compounds can be stimulated by allowing contaminated ground water to flow through an aquifer zone which has enhanced oxygen and nutrient conditions.	Moderate	High	No
In Situ Groundwater Treatment	Biological	Oxygen and/or Nutrient Enhanced Biodegradation (Biosparging)	Differs from biologically active zone in that oxygen (air) is injected upgradient of plume and allowed to migrate downgradient. In theory, this method can more rapidly reduce higher BTEX/PAHs concentrations in and immediately downgradient of the source. Nonhomogeneous hydrogeology will severely limit effectiveness.	Low	Low	No

TABLE 1 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR SOIL AND GROUND WATER REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

General Response Action	Technology Type	Process Option	Technical Implementability	Effectiveness in Attaining Target Remedial Goals	Relative Cost	Retain
In Situ Groundwater Treatment (cont.)	Chemical/Physical (cont.)	Intrinsic Remediation	A combination of natural biological, chemical, and physical removal mechanisms which occur to varying degrees on every site. Groundwater sampling at Area D indicates that this is a major, ongoing remediation process.	High	Low	Yes
		Air Sparging (volatilization)	Injection of air into contaminated aquifer creating a mass transfer of BTEX and highly sorptive PAHs into air bubbles and into vadose zone. Limited radius of influence and short-circuiting are common problems. Nonhomogeneous hydrogeology will limit effectiveness.	Low	Low	No
Aboveground Groundwater Treatment	Biological	Bioreactors	High flow rates require excessive retention times and large reactors. BTEX is often volatilized in these systems.	Moderate	High	No
	Chemical/Physical	Air Stripping	Cost-effective technology for removing varying concentrations of BTEX at higher flow rates and longer durations. Potential permitting for air emissions.	High	Moderate	Yes
		Activated Carbon	Cost effective for more dilute concentrations of BTEX/PAHs. Creates a carbon disposal problem.	High	High due to carbon cost	No
		UV/Ozone Reactors	High flow rates require excessive retention times and large, expensive reactors.	Moderate	High	No

TABLE 1 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR SOIL AND GROUND WATER REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

General Response Action	Technology Type	Process Option	Technical Implementability	Effectiveness in Attaining Target Remedial Goals	Relative Cost	Retain
Aboveground Groundwater Treatment (cont.)	Chemical/Physical (cont.)	Direct Discharge to Industrial Waste Water Treatment Plant (IWWTP)	Viable option when an IWWTP is available and capable of handling BTEX/PAHs and hydraulic loading. IWWTP not available for this site.	High	High	No
Treated Groundwater Disposal	Discharge to IWWTP or Sanitary Sewer	IWWTP	Viable option when an IWWTP is available and capable of handling BTEX/PAHs and hydraulic loading. IWWTP not available for this site.	High	High	No
		Sanitary Sewer	Viable option when access to sanitary sewer exists and hydraulic loading is acceptable. Sewer line near this site.	High	Low when sewer available	Yes
	Treated Groundwater Reinjection	Vertical Injection Wells	Not recommended due to clogging and high maintenance.	Moderate	High	No
		Injection Trenches	Require large trenches and can be subject to injection well permitting.	Moderate	High	No
	Discharge to Surface Waters	Storm Drains	Viable option but generally requires NPDES or other discharge permit. Storm drain not readily available.	High	Moderate Permitting Costs	No
Source Removal/Soil Remediation	Free Product Recovery	Dual-Pump Systems	Best suited for sites with >1 foot free product where aboveground groundwater treatment exists. Site has less than 1 foot of free product. Nonhomogeneous hydrogeology will limit effectiveness.	Low	High	No

TABLE 1 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR SOIL AND GROUND WATER REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

General Response Action	Technology Type	Process Option	Technical Implementability	Effectiveness in Attaining Target Remedial Goals	Relative Cost	Retain
Source Removal/Soil Remediation (cont.)	Free Product Recovery (cont.)	Skimmer Pumps/Bailers/ Wicks	Best suited for sites with <1 foot free product where groundwater pumping is undesirable. Nonhomogeneous hydrogeology will limit effectiveness.	Moderate	Low	Yes
		Total Fluids Pumping	Best suited for sites with thin saturated zones where excessive groundwater will not be pumped. Nonhomogeneous hydrogeology will limit effectiveness.	Moderate	High	No
		Bioslurping	Combined vapor extraction, bioventing, and free product recovery system has been operated at some sites with success.	Moderate	Intermediate	No
	Excavation/ Treatment of Soils	Excavation	Buildings, pipelines, and roads in source area prohibits excavation.	High	High	No
		Biological Landfarming	Buildings, pipelines, and roads in source area prohibits excavation.	Moderate	Moderate	No
		Thermal Desorption	Buildings, pipelines, and roads in source area prohibits excavation.	Moderate	High	No
	In Situ	Bioventing	Bioventing would be successful at Area D based on pilot test results.	High	Low	Yes
		Soil Vapor Extraction	Vapor extraction has been successfully implemented at other sites; however, off-gas treatment will probably be required.	High	High due to off-gas treatment	No

TABLE 1 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR SOIL AND GROUND WATER REMEDIATION
AREA D, ELLSWORTH AFB, SOUTH DAKOTA

General Response Action	Technology Type	Process Option	Technical Implementability	Effectiveness in Attaining Target Remedial Goals	Relative Cost	Retain
Source Removal/Soil Remediation (cont.)	*In Situ* (cont.)	Soil Washing	Additional pore volumes of water and/or surfactant solution are forced through aquifer material to enhance the partitioning of hydrocarbons into the groundwater. Creates special above ground treatment problems.	Moderate	High	No

- Intrinsic remediation of soil and groundwater contamination;
- Groundwater extraction in source area via an interceptor trench;
- Extracted groundwater treatment with air sparging;
- Treated groundwater discharge via sanitary sewer;
- Passive wicking for LNAPL removal; and
- Air injection bioventing in source area.

Because intrinsic remediation, and specifically biodegradation, has been effectively removing dissolved BTEX compounds from the groundwater and limiting downgradient migration, this ongoing remediation process can only be enhanced through a reduction of LNAPL and more concentrated dissolved BTEX in the vicinity of the source area surrounding Building 8215. Two candidate source-reduction technologies, passive wicking and bioventing, have been retained for additional analysis. Downgradient groundwater extraction via and interceptor trench was retained as an aggressive method of plume control. Each of these remediation approaches is described in greater detail, and their effectiveness is evaluated in Section 8 of this RAP.

4.1 REFERENCES

Downey, D.C. 1994. Bioventing Performance and Cost Summary. Proposal for Air Force Center for Environmental Excellence, Brooks Air Force Base, San Antonio, Texas. July.

Wiedemeier, T.H., J.T. Wilson, D.H. Kambell, R.N. Miller. 1994. US Air Force Guidelines for Successfully Supporting Intrinsic Remediation with an Example from Hill AFB. Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Groundwater Conference. Houston, TX. Pp 317-335.

Alternative 1 Cost Estimate

Ellsworth AFB - Area D
725521.04000

Anthony Rainsberger
(AJR)
6-12-95

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Capital Costs

Design/construct 4 Groundwater Monitoring Wells
(TD= 35' each) (Total liner feet = 140')

Design/Procure/Construct/Develop (173hr × $60/hr)	=$10,380
Drilling Subcontractor (140 LF × $70/LF)	=$ 9800
Per Diem (10 days × $ 90/day)	=$ 900
Travel	= $1000
Equipment Rental	= $500
Contingency (15%)	=$ 3400
	$ 25,980 Total

Soil Sampling in Source Area

No soil sampling necessary for Natural Attenuation

ⓐ Fundamental of Engineering, MC Potter, 1990 (7% discount rate in accordance with EPA Guideance for Conducting RI/FS Under CERCLA, 1988)

Alternative 1 Cost Estimate
Ellsworth AFB - Area D
725521.04000

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Annual / Biannual Cost

Annual Sampling Labor 80 hrs $60/hr 11 long-term monitoring wells + 2 QA/QC 13 samples	= $ 4800
Analytical Subcontractor 13 BTEX × $90ea 11 Naphthalene × $200 ea	= $3370
Supplies	= $500
Travel	= $1000
Per Diem ($90/day × 10days)	= $900
Office ODC	= $300
Contigency (10%)	= $1087
	$11,957 Total

Site Management

160 hr/yr × $60/hr — $9,600 Total

Summary of Costs

Capital = $25,980

Annual

Site Management (22 yrs)

$(P/A)^{7\%}_{22}$ = 11.061 ⓐ

9600 × 11,061 = $ 106,185

Sampling

see attached spreadsheet (sampling present worth calcs) = $ 96,972

Capital + Site Management + Sampling = Total = $229,137 ≅ 229,130

Present Worth Total Alternative 1

$229,130

Alternative 2 - Cost Estimate
Ellsworth AFB - Area D
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Capital Costs (Source Removal Technologies)

Design/Construct Bioventing System

Design/Procure/Construct/Test 300hr x $60/hr	=$ 18000
Materials and Equipment 5HP Blower $ 1,600 Enclosure 500 Pipe & Valves 444 LF x $ 5/LF + $ 500	=$ 4,820
Electrical Subcontractor	=$ 1000
Per Diem (32 days x $90/day)	=$ 2,880
Travel	=$ 2,000
Rental Equipment	=$ 1500
Contingency (%10)	=$ 3020
	$33,220 Total

Design/Construct Passive Wicking System

Design/Procure/ Installation	=$ 3,000
Materials and Equipment (10 wicks)	=$ 150
Per Diem (2 days x $90 day)	= $180
	$ 3,330

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Alternative 2 - Cost Estimate
Ellsworth AFB - Area D
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Install 4 GW monitoring wells (See Alternative 1) =$25,980 Total

Soil sampling in Source Area (After 2yrs)

Design/procure/sample Handling/Report
188 hrs. x $60/hr =$11 280

Rental Equipment (INCLUDING GEOPROBE) = $2,500
Analytical Subcontractor (24 BTEX @ $90 ea & 24 TPH @ $160 ea) = $6000
Per Diem (12 days @ $90/day) = $1080
Travel = $1000
Office ODC = $200
Contigency (10%) = $2,206
= $24,266

2yr present worth factor $(P/F)_2^{7\%}$ = 0.8734 × 24,266 ⇒ $21,194 Total

CAPITAL COSTS: $83,724 TOTAL

ANNUAL COSTS

Site Management (intrinsic remediation - See Alternative 1) = $9,600

Site Management for Bioventing/WICKING (EAFB PERSONNEL)

Bioventing	1 person 1 hr/wk	=	52 hrs/yr
	1 person 3 day/YR	=	24 hrs/yr
WICKING	1 PERSON 1 hr/wk	=	52 hrs/yr
			128 hrs/YR

$60/hr

= $7,680

GW Sampling Event (same as Alternative 1) = $11,957 checked: RAF

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Alternative 2 Cost Estimate
Ellsworth AFB - Area D
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Annual Costs (cont.)

Bioventing Power Usage

Bioventing blower = 5HP

total Power $5\ \text{HP} \times 745.7\ \frac{\text{Watts}}{\text{HP}} \times \frac{1\ \text{KW}}{1000\ \text{watts}} = 3.73\ \text{KW}$

assume system runs 365 days/yr & 24 hrs/day

$365\ \frac{\text{days}}{\text{yr}} \cdot 24\ \frac{\text{hrs}}{\text{day}} = 8760\ \frac{\text{hrs}}{\text{yr}}$

$3.73\ \text{KW} \cdot 8760\ \frac{\text{hrs}}{\text{yr}} = 32{,}661\ \frac{\text{KW}\cdot\text{hrs}}{\text{yr}} \times \frac{\$0.06}{\text{KW}\cdot\text{hrs}}$

$= \$1{,}960$

No equipment replacement required for 2yrs of operation

Summary of Costs

Capital Total = Bioventing + WICKING + Soilsampling + GW wells

= 33,220 + 3,330 + 25,980 + 21,194 = $83,724

Present Worth : Annual

Sampling cost
See attached spreadsheet (sampling present worth calcs.) = $96,972

Site Management (intrinsic Remediation) (22yrs) = $106,185
$9600 × 11.061

Site Management (Bioventing/WICKING)
2yrs operation → $(P/A)^{7\%}_{2} = 1.808$
$\$7{,}680/\text{yr} \times (P/A)^{7\%}_{2}$ = $13,885

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Alternative 2 - Cost Estimate
Ellsworth AFB - Area D
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Summary of Costs (cont)

✓ Power Usage = $1,960/yr

~2yrs operation $\longrightarrow (P/A)_2^{7\%} = 1.808$ @ = $3,544

1,808 × 1,960

Total Costs = Capital Costs + Present Worth (annual costs)

= $ 83,724 + $96,472 + $106,185 + $13,885 + $3,544

= $304,310 ≅ 304,300

Present Worth Total Alternative 2
$304,300.

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Alternative 3 - Cost Estimate
Ellsworth AFB - Area D
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Capital Costs

POA wells (see alternative 1)	= $ 25,980
Soil Sampling (see alternative 2)	= $ 21,194
Bioventing (see alternative 2)	= $ 33,220
PASSIVE WICKING (SEE ALTERNATIVE 2)	= $ 3,330

French Drain

Design/Procure/Const Managmt
design (10% of project costs) = $24,000
procurement 1 person 3 wks • 120 hrs x $60/hr = $7200
const management
project const. time = 65 days
+ 10 day set up/break down
600 hrs x 2 people
1200 hrs x $60/hr = $72,000

Construction/Materials/Equipment (SEE PAGE 4) = $240,000

Per diem 105 day (including weekends) = $18,900
x 2 people
210 days x $90/day

Travel = $4000

Contingency (20%) = $73,220

$ 439,320 Total

Annual Costs (25 yr life 15 gw monitoring wells)

Site Management (intrinsic remediation) = $9,600
(see Alternative 1)

Site Management (Bioventing/WICKING) = $7,680
(see Alternative 2)
128 hrs/yr x $60 hr

Site Management (GW treatment/F. Drain) = $15,120
GW Treatment = 200 hrs/yr
F. Drain (1 hr/wk) = 52 hrs/yr
252 hrs/yr X $60/hr

Sampling - similar per sampling event costs as alternative 1 except
4 additional BTEX & Naphthalene samples = 4 x 90 + 4 x 200 = 116
1160 + 11,957
= $13,117

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Alternative 3 - Cost Estimate
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Annual Cost (Cont.)

GW Treatment Sampling (see Alternative 2) = $8400

BIOVENTING Power Usage (5 HP - see Alternative 2)

$$\text{Total HP} = 5\ \text{HP} \times .7457\ \frac{\text{KW}}{\text{HP}} = 3.73\ \text{KW}$$

$$8760\ \frac{\text{hrs}}{\text{yr}} \cdot 3.73\ \text{KW} = 32{,}661\ \frac{\text{KW}\cdot\text{Hrs}}{\text{yr}} \times \frac{\$0.06}{\text{KWHr}}$$

$$= \$1{,}960$$

GW Treatment Power Usage (6HP see Alternative 2)

$$6\text{HP} \times .7457\ \frac{\text{KW}}{\text{HP}} = 4.4742\ \text{KW}$$

$$8760\ \frac{\text{hrs}}{\text{yr}} \times 4.4742\text{KW} = 39194\ \frac{\text{KW Hrs}}{\text{yr}} \times \frac{\$0.06}{\text{KW}\cdot\text{hr}}$$

$$= \$2352$$

Equipment Replacement

BIOVENTING - none 2yrs operation

GW Treatment

addition replacement equipment ⇒ 1 stripper / 10 yrs ⇒ 2 strippers @ $9000
1 Transfer pump / 5 yrs
2 pump × 4 changes ⇒ 8 Transfer pump @ $750

Summary of Costs

Capital Total = POA wells + soil sampling + Bioventing + WICKING + French Drain
= 25,980 + 21,194 + 33,220 + 3,330 + 439,320
= $ 523,044

Present Worth Calcs.

Sampling (see attach sampling present worth calcs. spread sheet) = $152,852

Site Management (intrinsic remediation) $(P/A)^{7\%}_{25} = 11.653$ ⓐ
$9{,}600 \times (P/A)^{7\%}_{25} = 111{,}869$ = $111,869

Site Management (Bioventing/WICKING) $(P/A)^{7\%}_{2} = 1.808$
$7{,}680 \cdot (P/A)^{7\%}_{2} =$ = $13,855

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Alternative 3 - Cost Estimate
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Summary of Cost (cont.)

Present Worth Costs: Site Management (F. Drain/G.W Treatment) $(P/A)^{7\%}_{25} = 11.653$

$\$15,120 \times (P/A)^{7\%}_{25} =$ = $176,193

Groundwater Treatment Sampling
$(P/A)^{7\%}_{25} = 11.653$
8400×11.653 = $97,885

BIOVENTING Power Usage
$(P/A)^{7\%}_{2} = 1.808$
$1,960 \times 1.808$ $3,544

GW Treatment Power Usage
$(P/A)^{7\%}_{25} = 11.653$
2352×11.653 = $27,408

Equipment Replacement
$(P/F)^{7\%}_{0} = 1$
$(P/F)^{7\%}_{5} = 0.71299$
$(P/F)^{7\%}_{10} = 0.50835$
$(P/F)^{7\%}_{15} = 0.36245$
$(P/F)^{7\%}_{20}$ 0.25842

1 stripper + 2 Transfer pumps @ year 0 in capital costs for systems

2 Transfer pumps @ year 5 = $(750) \times 2 \times .71299 = 1,069$

1 stripper & 2 Transfer pumps @ year 10 = $[(750) \times 2 + 9000] \times .50835 = 5,338$

2 Transfer pumps @ year 15 = $(750) \times 2 \times .36245$ = 544

1 stripper & 2 Transfer pumps @ year 20 = $[(750) \times 2 + 9000] \times .25842 = 2,713$

Total = $9,664

Total Cost = Capital + Present Worth (annual costs)

= 523,044 + 152,852 + 111,869 + 13,855 + 176,193 + 97,885 + 3,544 + 27,408 + 9,664 = 1,116,314 ≅ 1,116,300

Present Worth Total Alternative 3

$ 1,116,300

Checked by RAF

DCD 11/28/95

Alternative 3 - Cost Estimate
Ellsworth AFB - Area D
725521.04000

AJR
6-13-95

Page 4 of 4

Materials & Construction Costs for French Drain

Earthwork	$180,000
Dewatering during Earthwork	$ 6,200
Geotextile filter	$ 1,200
PVC liner	$ 4,000
Filter & liner installation	$20,000
sump installation	$1,500
submersible pump	$ 3,000
pvc drain pipe	$1,500
additional controls	$2,000
surge tank (5000 gal)	6200
transfer pump (1/4 Hp)	$1000
5% mob/Demob	$11,330

total ≈ $240,000

PEATWICK™

Passive Hydrocarbon Recovery System

The **Peatwick™** is a passive recovery system designed to provide continuous recovery of floating hydrocarbons from groundwater monitoring wells at a fraction of the cost of standard mechanical or manual bailing systems.

The **Peatwick** absorbs floating hydrocarbons with a hydrophobic organic material and provides continuous recovery through a capillary action which draws hydrocarbons into the "wick" until the "wick" reaches saturation.

Applications:

Interim Response

The **Peatwick** is ideal as an interim response measure when floating hydrocarbons are encountered during groundwater investigations. By simply installing a **Peatwick** in the contaminated well, product recovery can commence while a permanent remedial system is designed.

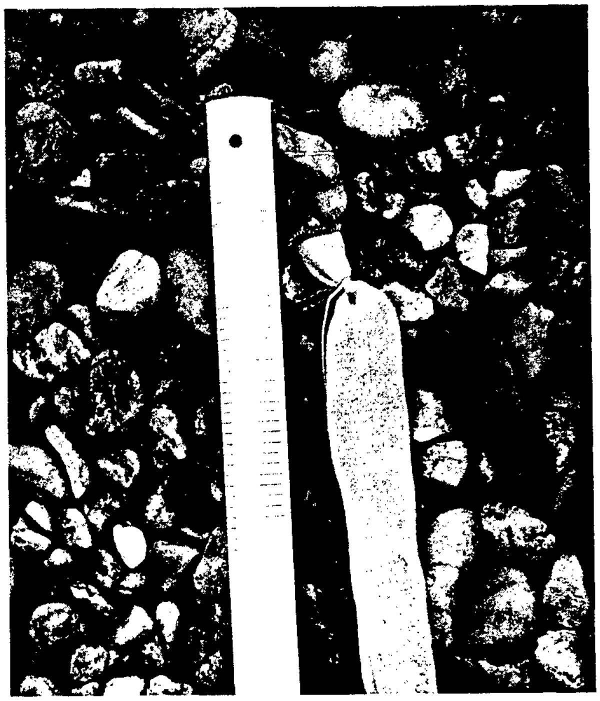
Remote Locations

The **Peatwick** has also been successfully used for product recovery at remote locations. Sites that either lack on-site utilities or require considerable travel to access have been found to be suited for the **Peatwick** system.

Marginal Product Thickness

The **Peatwick** is also used when floating hydrocarbon thicknesses are less than 1 inch. In these situations both manual and mechanical recovery methods are not practical but regulatory response requires some action.

4" WELL

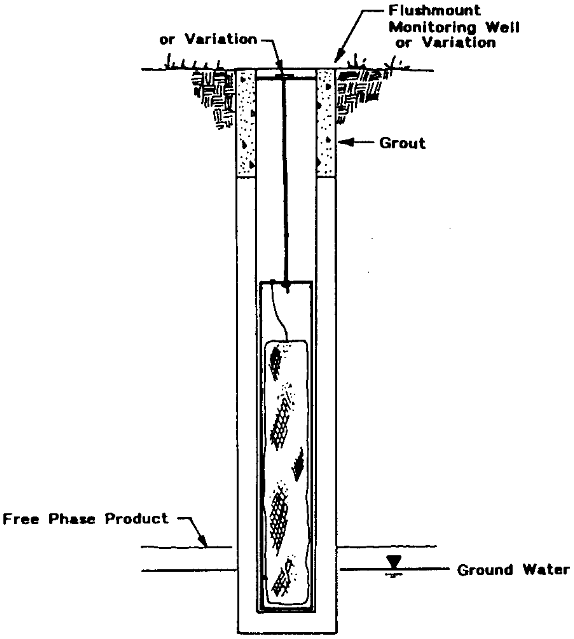


2" WELL

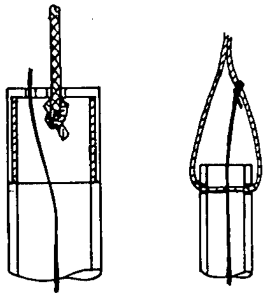
Peatwick™ Specifications

Absorbent Material - **Peatwick**™ systems utilize a dehydrated peatmoss. The dehydration process creates a porous structure with an affinity for hydrocarbon absorption while repelling water. This process also creates a natural capillary action which draws hydrocarbons into the "wick" and provides continuous recovery until the "wick" becomes saturated. The **Peatwick** absorbs approximately one gallon of hydrocarbons per pound of absorbent material.

Disposal Options - (1) The **Peatwick** absorbent material has passed the TCLP test with hydrocarbons and other liquids, so it is compatible with landfilling, when regulations permit. (2) Used peatwicks can also be incinerated. The absorbent material has an original heating value of about 9000 BTUs per pound (excluding hydrocarbons) and an ash residue of less than 5%. (3) Used peatwicks have also been incorporated as a medium in ex-situ bioremediation systems.



DETAIL OF 'PEATWICK'™ INSTALLATION



HANGER DETAIL

Peatwick	2" Wells Unit Price	4" Wells Unit Price
Canisters **Part No.**	$ 30.00 **001**	$ 60.00 **002**
Wicks **Part No.**	$ 15.00 **003**	$ 25.00 **004**
Absorbtion Capaciity **(maximum)**	**1 GAL.**	**3 GAL.**

For Information, contact:

ENVIRONMENTAL BASICS COMPANY

P.O. Box 453 Shillington, PA 19607

PHONE: 610-796-9102

Save Up to 70% on Free Product Recovery

Why pay the excessive costs for manually bailing wells with marginal product thickness??

How can the costs for managing free product recovery at remote locations be significantly reduced??

How can State Interim Response measures be satisfied with a limited budget??

The PEATWICK™
Passive Hydrocarbon Recovery System

- *Low Cost*
- *Simple to Install*
- *No utility requirements*

Environmental Basics Company
P.O.Box 453
Shillington, PA 19607
610-796-9102

APPENDIX I

SITE SAMPLING AND ANALYSIS PLAN

SITE SAMPLING AND ANALYSIS PLAN

FOR

REMEDIAL ACTION PLAN AND LONG-TERM MONITORING PLAN RISK-BASED APPROACH TO REMEDIATION AREA D, ELLSWORTH AFB, SOUTH DAKOTA

Prepared for:

AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE
(AFCEE) TECHNOLOGY TRANSFER DIVISION (ESR)
BROOKS AIR FORCE BASE, TEXAS 78235-5000

USAF CONTRACT F41624-93-C-8044

June 1995

Prepared by:

PARSONS ENGINEERING SCIENCE, INC.
1700 Broadway, Suite 900
Denver, Colorado 80290

The purpose of this site-specific sampling and analysis plan (SAP) is to provide the procedures to be followed when collecting data in support of the long-term monitoring plan (LTMP) for the risk-based approach to remediation at Area D. Details on analytical requirements, desired quantitation (detection) limits, and proposed sampling locations are identified within section 10 of the Remedial Action Plan (RAP). The need to collect additional samples to meet quality assurance requirements are described in the program quality assurance project plan (QAPP) (Appendix J). Specific quality assurance sampling requirements for Area D are summarized herein as part of the site-specific sampling procedures. These additional samples will be used to determine the precision, accuracy, completeness, and representativeness of the final data set.

Soil gas sampling is described in Section 1; soil flux sampling is described in Section 2; drilling, soil sampling, lithologic logging, and groundwater monitoring well installation procedures are described in Section 3; and groundwater sampling procedures are described in Section 4; and field quality assurance/quality control (QA/QC) samples are described in Section 5.

1.0 SOIL GAS SAMPLING

Soil gas will be used as an indicator of subsurface hydrocarbon contamination and to assess the effectiveness *in situ* bioventing in removing source contamination at the site. The use of soil gas to delineate potential subsurface contamination and to determine bioventing effectiveness has several economic and technical advantages over more traditional drilling and soil sampling techniques. The labor and equipment cost can be significantly less than a conventional drilling and sampling team. Many new hydraulically driven, multi-purpose probes can be used for soil gas sampling. These probes can be advanced as quickly as conventional augers and do not produce drill cuttings which can require expensive analysis and disposal. Further, soil gas sampling can represent the average chemistry of several cubic feet of soil as compared to a discrete soil sample, which can only describe a few cubic inches of the subsurface. This is of particular importance in risk-based remediation projects where the extent of COC contamination and the degree of removal of COCs can most accurately be determined by using multiple soil gas sampling locations.

The test equipment and methods that will be required to conduct field soil gas sampling as part of the risk-based remediation at this site are described fully in the AFCEE document *Using Soil Gas Surveys to Determine Bioventing Feasibility and Natural Attenuation Potential* (AFCEE, 1994). In summary, soil gas sampling will be conducted initially to establish a contaminant concentration baseline for the site. Sampling will then be conducted every 6 months during system operation to assess contaminant removal rates. Oxygen utilization and carbon dioxide production will also be measured at this time to calculate biodegradation rates. Once soil gas contaminant concentrations and respiration rates indicate that subsurface contaminants have been biodegraded, confirmatory soil samples will be collected. This is anticipated to take approximately 2 years.

Soil gas sampling will be conducted at the existing 4-inch diameter air injection wells and three multi-depth vapor monitoring points installed during the pilot-scale test at Area D. Samples will be collected using air-tight well tops or, in the case of the vapor monitoring points, existing ball valves and hose barbs with flexible tubing.

Gaseous concentrations of carbon dioxide and oxygen will be analyzed onsite using an O_2/CO_2 analyzer. The analyzer will generally have an internal battery-powered sampling pump and range settings of 0 to 25 percent for both oxygen and carbon dioxide. Before analyzing samples, the analyzer must be checked for battery charge level. The analyzer will also be calibrated daily using atmospheric conditions of oxygen (20.9 percent) and carbon dioxide (0.05 percent) and a gas standard containing 0.0 percent oxygen and 5.0 percent carbon dioxide.

Total volatile hydrocarbon (TVH) concentrations will be used as the primary screening tool at this site. The TVH analyzer used at Area D will be capable of measuring hydrocarbon concentrations in the range of 1 to 20,000 parts per million, volume per volume (ppmv). The analyzer must also distinguish between methane and non-methane hydrocarbons. The battery charge level on the TVH analyzer will be checked prior to analysis of each collected soil gas sample. The TVH analyzer will also be calibrated daily using a hexane calibration gas.

All soil gas samples taken during system monitoring at Area D will be collected using 3-liter Tedlar™ bags and vacuum chambers. The soil gas sample will then be analyzed by attaching the O_2/CO_2 and TVH analyzers directly to the Tedlar™ bag. Sample locations identified for analytical compound-specific analysis will be re-sampled using 3-liter Tedlar™ bags and vacuum chambers. The sample will then be transferred to 1-liter SUMMA™ canisters and shipped to the laboratory for compound-specific analysis using EPA Method TO-3 (see Table 2.1 in the RAP).

Field QA/QC procedures for soil gas will include collection of one field duplicate for every 10 samples collected (e.g., frequency of 10 percent), use of analyte-appropriate containers, and chain-of-custody procedures for sample handling and tracking. All samples to be transferred to the analytical laboratory for analysis will be clearly labeled to indicate sample number, location, matrix (e.g., soil gas), and analyses requested. Samples will be preserved in accordance with the analytical methods to be used.

All field sampling activities will be recorded in a bound, sequentially paginated field notebook in permanent ink. All sample collection entries will include the date, time, sample locations and numbers, notations of field observations, and the sampler's name and signature.

Soil gas QA/QC sampling for analytical purposes will include field duplicates at a frequency of 10 percent. However, the laboratory should also plan to conduct one matrix spike analysis, one laboratory control sample, and one laboratory blank test for each specific analysis requested for soil gas (i.e., required only once for soil gas extracted via soil gas monitoring point or obtained via flux chamber).

2.0 SOIL FLUX SAMPLING

Several soil flux tests will be conducted at the site prior to bioventing system startup to determine the natural background emissions from the site. Soil flux tests will also be performed at the sample same locations during the first day of system operation. The purpose of these flux tests is to estimate potential air quality impacts from COC emissions forced from contaminated environmental medium by the subsurface air injection associated with bioventing. Flux samples will be collected at Area D using the procedures outlined in EPA guidance *Measurement of Gaseous Emissions Rates from Land Surfaces Using a Emission Isolation Flux Chamber* (EPA, 1985). The use of a flux box is the preferred method of measurement of surface emission rates of volatile contaminants. A flux box is used to isolate a known surface area from the ambient air, collect surface emissions, and mix the collected emissions with "sweep" air introduced into the chamber at a known flow rate. Data from the flux box can then be combined with a simple dispersion model to identify potential ambient air contamination impacts.

The procedures contained within EPA's protocol document on measuring emission rates (i.e., *Measurement of Gaseous Emission Rates from Land Surfaces using an Emission Isolation Flux Chamber* (EPA/600/8-86/008)) will be followed. In summary, gaseous emissions will be collected from an isolated surface area using a flux chamber and monitored using both "real-time" and discrete methods. Real-time measurements will be made with a portable hydrocarbon analyzer to determine when the chamber reaches steady-state conditions. Discrete samples will then be collected for chemical analysis.

To reduce the potential for cross-contamination, which can occur whenever high level or low level samples are sequentially analyzed, the flux chamber will be purged and tested with a blank after each sample is conducted. Emission tests will only be conducted when soil moisture levels are normal. Increased ground moisture as a result of rain or heavy dew can bias (lower) emission rates.

The sweep air to be used will be dry, organic free air equal to or better than commercial ultra high purity grade (< 0.1 ppmv total hydrocarbon content). Discrete samples will be collected in SUMMA™ canisters and analyzed using EPA Method TO-3 to identify BTEX concentrations.

Field QA/QC procedures for soil flux sample will be identical to those required for soil gas. QA/QC requirements include collection of a field duplicate at a frequency of 10 percent, use of analyte-appropriate containers, and chain-of-custody procedures for sample handling and tracking. All samples to be transferred to the analytical laboratory for analysis will be clearly labeled to indicate sample number, location, matrix (e.g., soil gas), and analyses requested. Samples will be preserved in accordance with the analytical methods to be used.

All field sampling activities will be recorded in a bound, sequentially paginated field notebook in permanent ink. All sample collection entries will include the date, time, sample locations and numbers, notations of field observations, and the sampler's name and signature.

Soil flux QA/QC sampling includes collection of a field duplicate at a frequency of 10 percent. However, the laboratory should also plan to conduct one matrix spike analysis, one laboratory control sample, and one laboratory blank test for each specific analysis requested for soil gas (i.e., required only once for soil gas extracted via soil gas monitoring point or obtained via flux chamber).

3.0 DRILLING, SOIL SAMPLING, AND GROUNDWATER MONITORING WELL INSTALLATION

To monitor contaminant plume migration at Area D, four additional groundwater monitoring wells will be installed downgradient of Area D. The following sections describe the proposed well locations and completion intervals, equipment decontamination procedures, drilling and soil sampling, well installation, well development procedures, and well location and datum surveying. All drilling, soil sampling, and well installation will proceed from areas suspected to be least contaminated to areas suspected to be more contaminated.

3.1 Well Locations and Completion Intervals

Three wells will be installed approximately 1,200 feet downgradient of Area D to establish an operational point-of-action (POA). If site-related contaminants are detected at concentrations exceeding promulgated state groundwater standards at any these POA wells, contingency actions will be considered as outlined in Section 9.3 of the RAP. One additional well will be installed approximately 800 feet downgradient to monitor the future migration of the contaminant plume. All additional wells will be screened from 3 feet above the groundwater table to competent Pierre Shale. Based on previous well installation activities at Area D, a 10-foot screened interval should be sufficient. Because the locations of all four additional wells are significantly distant from Area D, no accurate predictions of depth to groundwater or bedrock can be made. The new well locations were selected to intercept the plume based on predicted future movement. Based on plume migration predictions, contaminants exceeding groundwater quality standards should never reach the three POA wells. Figure 10.1 in the RAP shows the proposed well locations.

3.2 Drilling and Soil Sampling Procedures

This subsection addresses the procedures for drilling soil borings that will be used for soil sampling and completed as new wells. All new monitoring wells will be installed in accordance with general procedures outlined in Section 8.5 of *A Compendium of Superfund Field Methods* (EPA, 1987).

3.2.1 Pre-Drilling Activities

All necessary digging, drilling, and well installation permits will be obtained by Ellsworth AFB personnel prior to Parsons ES mobilizing to the field. In addition, all utility lines will be located and proposed drilling locations cleared prior to any drilling activities.

3.2.2 Equipment Decontamination Procedures

Water to be used in drilling, equipment cleaning, or grouting will be obtained from one of the base's onsite water supplies. Ellsworth AFB personnel will assist Parsons ES field personnel in locating a suitable source. Water use approval will be verified by contacting the appropriate facility personnel. Only potable water will be used for the activities listed above. A decontamination water blank will be collected from the potable water source. The procedures for the collection of the decontamination water blank will be described in Section 5. The Parsons ES field hydrogeologist will make the final determination as to the suitability of site water for these activities.

Prior to arriving at the site, and between each drilling site, the drill rig, augers, drilling rods, bits, casing, samplers, tools and other downhole equipment will be decontaminated using a high-pressure, steam/hot water wash. Only potable water will be used for decontamination.

During drilling operations, the drill rig, augers, and any down-hole drilling and/or sampling equipment will be decontaminated at a temporary decontamination pad that will be set up at Area D. The temporary decontamination pad will be constructed in a manner so as to contain all decontamination fluids. All decontamination fluids generated at the temporary decontamination pad will be placed in 55-gallon drums. The decontamination fluids will be disposed of following the procedures presented in Section 4.3.

All sampling tools will be cleaned onsite, prior to use and between each sampling event, with a clean water/phosphate-free detergent mix and a clean water rinse. All well completion materials that are not factory sealed will be cleaned onsite prior to use with a high-pressure, steam/hot water wash using approved water. Materials that cannot be cleaned to the satisfaction of the Parsons ES field hydrogeologist will not be used. All decontamination activities will be conducted in a manner so that the excess water will be controlled and not allowed to flow into any open borehole.

If contaminated soils are encountered during drilling (based on visual, olfactory, or volatile organic analyzer indications), and the potential for cross-contamination is anticipated, drilling will be stopped and modified drilling procedures will be implemented to prevent the transfer of contaminants to deeper strata.

Fuel, lubricants, and other similar substances will be handled in a manner consistent with accepted safety procedures and standard operating practices. Well completion materials will not be stored near or in areas which could be affected by these substances. The drill rigs will not be allowed onsite unless they are free from leaks in any hydraulic lines, and are free of any exterior oil and grease.

Surface runoff such as miscellaneous spills and leaks, precipitation, and spilled drilling fluid will not be allowed to enter any boring or well either during or after drilling/well construction. To prevent this from happening, starter casing, recirculation tanks, berms around the borehole, and surficial bentonite packs, as appropriate, will be used.

3.2.3 Drilling and Soil Sampling

Drilling in unconsolidated soils will be accomplished using hollow-stem augers. The borings will be drilled and continuously sampled to the proposed total depth of the monitoring well. For installation of groundwater monitoring wells, the auger ID will not be less than 4 inches. Determination of well completion details will be at the discretion of the Parsons ES field hydrogeologist.

If subsurface conditions are such that the planned drilling technique does not produce acceptable results (e.g. unstable borehole walls or poor soil sample recovery) another technique deemed more appropriate to the type of soils present will be used. Any alternate soil sampling procedure used must be approved by the Parsons ES field hydrogeologist and will be appropriate for the subsurface lithologies present at the site.

Continuous soil samples will be obtained using 5-foot long continuous core barrel or another similar method judged acceptable by the Parsons ES field hydrogeologist. Samples will be continuously collected in 5-foot intervals from the ground surface to competent bedrock. The Parsons ES field hydrogeologist will identify which samples from the continuous sampling device will be submitted for chemical analysis. Only soils that exhibit possible contamination will be retained for chemical analysis. If no evidence of contamination is found, a sample will be collected from approximately 1 foot above the beginning of the saturated zone. Soil samples which may be retained for chemical analysis will be placed in sample containers immediately after the core barrel is opened. A maximum of two soil samples for chemical analysis will be collected per borehole. All soil cores will be evaluated for lithologic characteristics, however. All soil samples collected will be removed from the continuous sampler and placed on clean aluminum foil for logging.

Every 2-foot interval of soil sample recovered will be subsampled, composited, and placed in a clean container for PID or similar hydrocarbon vapor analyzer headspace measurements for VOCs. Representative portions of the soil samples collected for the headspace procedure will be quickly transferred to the sample containers, which will be sealed and held for 15 minutes at an ambient temperature of 65 degrees Fahrenheit (°F) or greater. Semiquantitative measurements will be made by puncturing the container seal with the PID probe and reading the concentration of the headspace gases. The PID relates the concentration of total VOCs in the sample to an isobutylene calibration standard. The PID will be calibrated daily to 100 parts per million, volume per volume of isobutylene. It is anticipated that headspace measurements will be performed on all samples collected during the drilling operations to determine which soil samples will be submitted for chemical analysis. The PID will also be used to monitor the worker breathing zone.

As a check on the quality of field sampling activities (sampling, containerization, shipment, and handling) QA/QC trip blanks, field blanks, equipment rinseate samples, and field duplicates will be sent to the laboratory. QA/QC sampling will include duplicates for soil samples at a frequency of 10 percent, equipment rinseate samples at a frequency of 10 percent, one field blank per sampling event, and a trip blank for each individual cooler sent to the analytical laboratory. The procedures for the collection of field QA/QC samples are discussed below in Section 5. Laboratory QA/QC procedures will include one matrix spike analysis, one laboratory control sample, and one laboratory blank test for each specific analysis requested.

The Parsons ES field hydrogeologist will be responsible for observing all drilling and well installation activities, maintaining a detailed descriptive log of subsurface materials recovered, photographing representative samples, and properly labeling and storing samples. An example of the proposed geologic boring log form is presented in Figure 1. The descriptive log will contain:

- Sample interval (top and bottom depth);
- Sample recovery;
- Presence or absence of contamination;
- Soil or rock description, including: relative density, color, major textural constituents, minor constituents, porosity, relative moisture content, plasticity of fines, cohesiveness, grain size, structure or stratification, relative permeability, and any other significant observations;
- Lithologic contacts: the depth of lithologic contacts and/or significant textural changes will be measured and recorded to the nearest 0.1 foot (1 inch); and
- Determination on whether soil sample will be submitted for chemical analysis or segregated as uncontaminated medium.

3.2.4 Minimization and Management of Drilling Residuals

Drilling activities will generate soil cuttings requiring proper handling and, if contaminated, proper disposal. Based on data from previous soil sampling efforts at the site, contamination outside the source area only exists in the narrow smear zone above the groundwater surface. Since all four proposed wells are downgradient of the contaminant plume, it is anticipated that contaminated soil will not be encountered. If contaminated soils are encountered, care will be taken to segregate them clean soils. Soils will be screened using a PID or similar hydrocarbon vapor analyzer. This limited drilling event will generate approximately 1.5 cubic yards of soil. All soils will be placed in a lined roll-on/roll-off box until analytical samples can be collected. If composite samples collected from the box show that the drill cuttings are clean, the soil will be spread on the ground surface in the vicinity of the newly installed wells. If the drill cuttings are contaminated with petroleum hydrocarbons, the soil will be placed in an on-Base land farm until contaminant concentrations reach acceptable levels.

3.3 Groundwater Monitoring Well Installation

Groundwater monitoring wells will be installed in each of the four soil borings completed at Area D. Except where specified, the entire thickness of the shallow aquifer will be screened. Detailed well installation procedures are described in the following paragraphs. A typical well completion diagram is included as Figure 2.

3.3.1 Well Material Decontamination

Well completion materials will be inspected by the Parsons ES field hydrogeologist and determined to be clean and acceptable prior to use. If not factory sealed, casing, screen, and casing plugs and caps will be cleaned with a high-pressure, steam/hot water cleaner using approved water prior to use. Prepackaged sand, bentonite, and Portland®

Sheet of

GEOLOGIC BORING LOG

BORING NO. ______________________
CLIENT: ______________________
JOB NO.: ______________________
LOCATION: ______________________
GEOLOGIST: ______________________
CONTRACTOR: ______________________
RIG TYPE: ______________________
DRLG METHOD: ______________________
BORING DIA.: ______________________
DRLG FLUID ______________________
DATE SPUD: ______________________
DATE CMPL: ______________________
ELEVATION: ______________________
TEMP.: ______________________
WEATHER: ______________________
COMMENTS: ______________________

Elev. (ft.)	Depth (ft.)	Pro-file	US CS	Geologic Description	Samples		Sample Type	Penet. Res.	Remarks
					No.	Depth (ft)			TIP = Bkgrnd/Reading (ppm)
	1								
	5								
	10								
	15								
	20								
	25								
	30								

sl - slight
tr - trace
sm - some
& - and
@ - at
w - with

v - very
lt - light
dk - dark
bf - buff
brn - brown
blk - black

f - fine
m - medium
c - coarse
BH - Bore Hole
SAA - Same As Above

SAMPLE TYPE

D - DRIVE
C - CORE
G - GRAB

C Core recovery

Core lost

Water level drilled

Figure 1

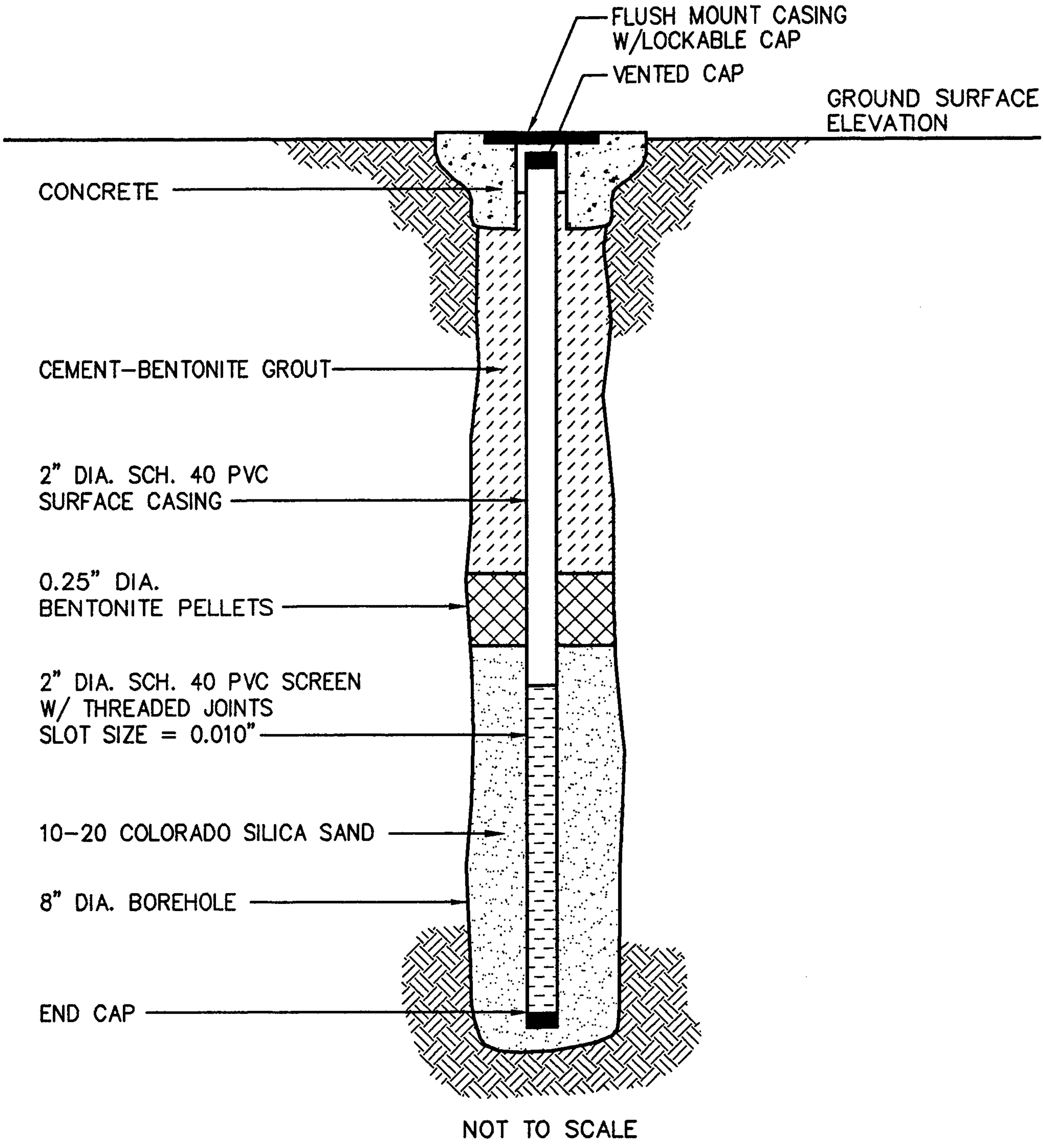


FIGURE 2

TYPICAL MONITORING WELL COMPLETION DIAGRAM

Remedial Action Plan
Risk-Based Approach to Remediation
Area D, Ellsworth AFB, South Dakota

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

K:\ELLSWRTH\95DN0910, 06/08/95 at 12:35

cement will be used in well construction, and the bags will be inspected for possible external contamination before use. Materials that cannot be cleaned to the satisfaction of the Parsons ES field hydrogeologist will not be used.

3.3.2 Well Casing

Upon completion of drilling to the proper boring termination depth, a monitoring well casing will be installed. Well construction details will be noted on a Monitoring Well Installation Record form, as shown in Figure 3. This information will become part of the permanent field record for the site. Blank well casing will be constructed of Schedule 40 polyvinyl chloride (PVC) with an ID of 2 inches. All well casing sections will be flush-threaded; glued joints will not be used. The casing at each well will be fitted with a threaded bottom plug and a top cap constructed of the same type of material as the well casing. The top cap will be vented to maintain ambient atmospheric pressure within the well casing.

The Parsons ES field hydrogeologist will verify and record the boring depth, the lengths of all casing sections, and the depth to the top of all well completion materials placed in the annulus casing and borehole wall. All lengths and depths will be measured to the nearest 0.1 foot.

3.3.3 Well Screen

Well screens will be constructed of flush-threaded, Schedule 40 PVC with an ID of 2 inches. The screens will be factory slotted with 0.010-inch openings. Each well will be screened so that seasonal fluctuations of the water table can be measured. The water level in the unconfined aquifer will be allowed to fluctuate within the screened interval. The position of the screen will be selected by the Parsons ES field hydrogeologist after consideration is given to the geometry and hydraulic characteristics of the stratum in which the well will be screened.

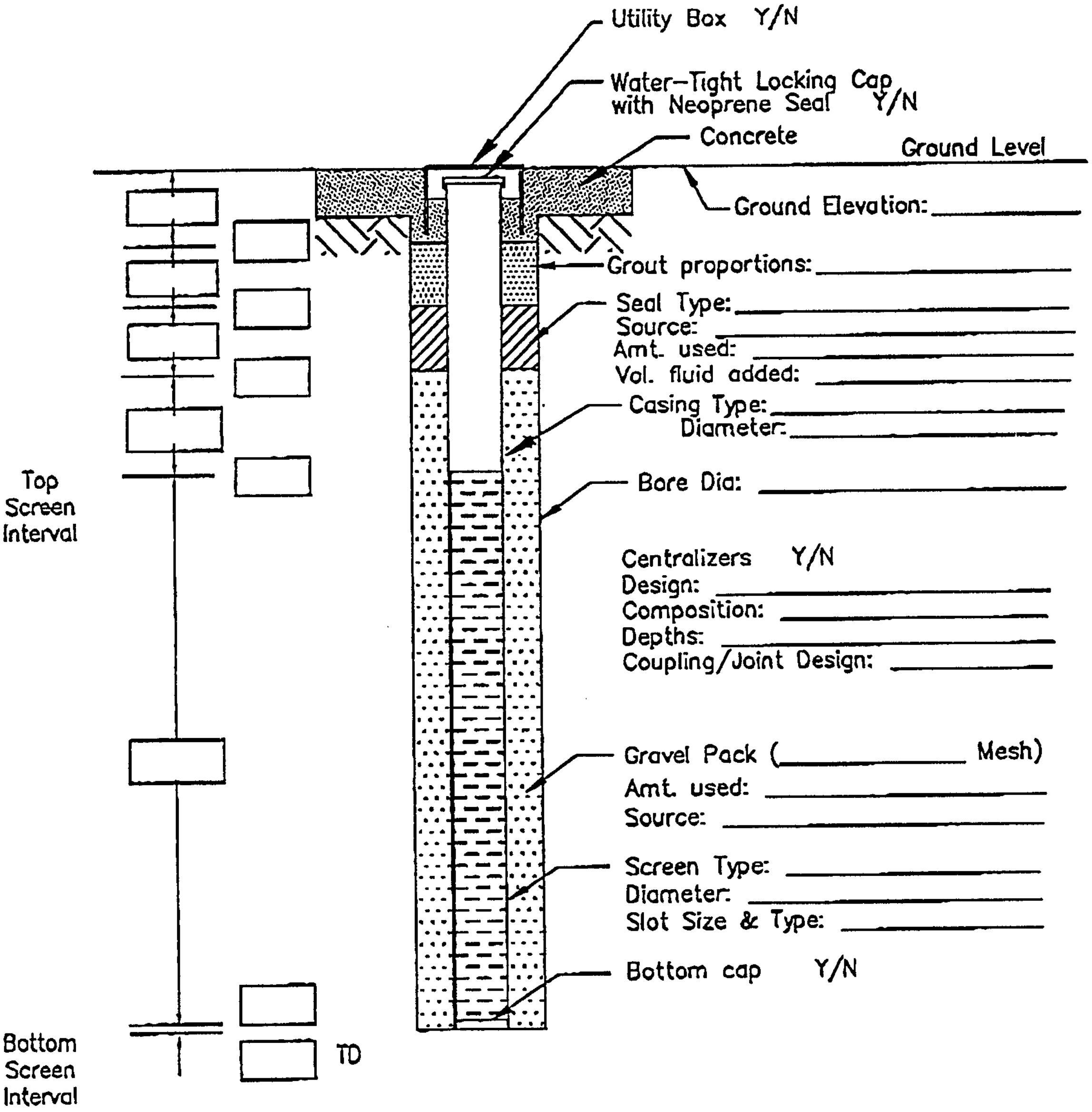
3.3.4 Sand Filter Pack and Annular Sealant

A graded sand filter will be placed around the screened interval and will extend at least 2 feet above the top of the screen. The sand filter will consist of 10-20 silica sand. An annular seal will be placed above the gravel pack using sodium bentonite pellets. The pellet seal will be a minimum of 2 feet thick and will be hydrated in place with potable water. The pellet seal will be overlain by a Portland® cement/sodium bentonite grout that will extend from the top of the pellet seal to approximately 3 feet bgs. The Portland® cement/sodium bentonite grout will consist of one 94-pound sack of cement and about 5 pounds of bentonite for each 7 gallons of water used. The bentonite content of the cement/bentonite will not exceed 8 percent by dry weight. The grout will be overlain with concrete to the ground surface. To reduce heaving of the newly-installed monitoring well caused by freeze-thaw processes, it is imperative that the uppermost concrete seal extend to at least the maximum frost line.

WELL CONSTRUCTION FORM

Installation:
Site:
Well ID:
Comp. started / / (: m)

Project no.
Drilling contractors:
Comp. finished: / / (: m)



Utility Box Y/N
Water-Tight Locking Cap with Neoprene Seal Y/N
Concrete
Ground Elevation:
Grout proportions:
Seal Type:
Source:
Amt. used:
Vol. fluid added:
Casing Type:
Diameter:
Bore Dia:

Centralizers Y/N
Design:
Composition:
Depths:
Coupling/Joint Design:

Gravel Pack (Mesh)
Amt. used:
Source:

Screen Type:
Diameter:
Slot Size & Type:

Bottom cap Y/N

Figure 3

3.3.5 Flush-Mount Protective Cover

Each monitoring well will be completed with an at-grade (flush-mount) protective cover. In areas where pavement is present, the at-grade cover will be cemented in place using concrete which will be blended to the existing pavement. In areas where pavement is not already present, a 6-inch thick, 4-foot-diameter concrete pad will be constructed around the protective cover. In either case, the concrete immediately surrounding the well cover will be sloped gently away from the protective casing to facilitate runoff during precipitation events.

3.4 Well Development

Before any new well can be considered in proper condition for monitoring water levels or taking water samples, it must be developed. Development removes sediment from inside the well casing and flushes fines, cuttings, and drilling fluids from the sand pack and the portion of the formation adjacent to the well screen. If a well is grouted prior to development, well development will occur no sooner than 48 hours after grouting of the annulus is completed.

Well development will be accomplished using dedicated disposable bailers or a peristaltic pump. The bailer or pump will be lowered to the bottom of the well so that fines which have accumulated in the bottom are agitated and removed from the well in the development water.

Development will be continued until a minimum of three casing volumes of water have been removed from the well and the water pH, temperature, and specific conductivity have stabilized. Temperature, pH and specific conductivity will be monitored during development (one reading for each parameter per well volume). Pumping will continue until these parameters have stabilized to within 10 percent among three consecutive readings and the water is clear and free of fines. The pH and specific conductivity meters will be calibrated on a daily basis. The pH meter will be calibrated by laboratory-prepared standard solutions following the manufactures calibration procedures. The specific conductivity meter will be calibrated using laboratory-prepared known conductivity solutions. If the development water still is turbid after removal of three casing volumes, development will be continued until the water becomes clear or the turbidity of the water produced has been stable after the removal of several casing volumes.

The development procedure specifies that three casing volumes of water be removed from the well. However, some wells completed in marginal aquifers will go dry during well development prior to the recovery of three casing volumes. In these low-productivity wells, development activity may have to be staged over a period of time to allow water to refill the well bore. In the event three casing volumes of water cannot be recovered, the water volume recovered will be noted in the development records.

All well purge water will be placed in 55-gallon drums supplied by the drilling subcontractor. Ellsworth AFB will be responsible for sampling, laboratory analysis and disposal of any contaminated or potentially contaminated purge and development water. Drums will be staged and temporarily stored onsite as directed by Ellsworth AFB personnel.

3.5 Well Development Records

A record of well development will be maintained for each well. The well development record will be maintained in a bound field notebook by the field hydrogeologist. Figure 4 is an example of the well development record. A summary well development record form will be prepared for each well and will become part of the written record for the site. Development records will include:

- Well number;
- Date and time of development;
- Development method;
- Predevelopment water level and well depth;
- Volume of water produced;
- Description of water produced;
- Post-development water level and well depth; and
- Field analytical measurements, including pH and specific conductivity.

3.6 Water Level Measurements

Water levels at all wells will be measured within a short time interval so that the water-level data are comparable. Water levels in the new wells will not be measured until they are developed and the water level has stabilized. The depth to water below the measurement datum will be made using an oil/water interface electric probe to the nearest 1/8 inch (0.01 foot). The oil/water interface probe will be decontaminated prior to use, and between each measurement, following the decontamination procedures presented in Section 4.3.

3.7 Well Location and Datum Survey

The location and elevation of the new wells will be surveyed by a registered surveyor soon after well completion. Horizontal locations will be measured relative to the state plane coordinate system for the State of South Dakota. Horizontal coordinates will be measured to the nearest 0.01 foot. Vertical location of the ground surface adjacent to the well casing, the measurement datum (top of the interior casing), and the top of the outer well casing will be measured relative to a USGS MSL datum. The ground surface elevation will be measured to the nearest 0.1 foot, and the measurement datum, outer casing, and surveyor's pin (if present) elevation will be measured to the nearest 0.01 foot.

3.8 Site Restoration

After well installation and sampling is complete, each well site will be restored as closely to its original condition as possible.

Well Development Record

Page__ of__

Job Number__________________ Job Name__________________
Location__________________ By__________________ Date________
Well Number__________________ Measurement Datum__________________

Pre-Development Information Time (Start):

Water Level: Total Depth of Well:

Water Characteristics

Color__________________ Clear Cloudy
Odor: None Weak Moderate Strong
Any Films or Immiscible Material__________________
pH__________ Temperature(°F °C) __________
Specific Conductance(µS/cm)__________________

Interim Water Characteristics

Gallons Removed

pH

Temperature (°F °C)

Specific Conductance(µS/cm)

Post-Development Information Time (Finish):

Water Level: Total Depth of Well:

Approximate Volume Removed:

Water Characteristics

Color__________________ Clear Cloudy
Odor: None Weak Moderate Strong
Any Films or Immiscible Material__________________
pH__________ Temperature(°F °C) __________
Specific Conductance(µS/cm)__________________

Comments:

Figure 4

4.0 GROUNDWATER SAMPLING

This section describes the scope of work required for collecting groundwater samples from the 11 monitoring wells in the long-term monitoring well network. All water samples collected from groundwater monitoring wells will be obtained using either disposable bailers or a thoroughly decontaminated peristaltic pump and new flexible tubing. Equipment blanks will be collected to assure that all equipment is properly cleaned. In order to maintain a high degree of quality control during this sampling event, the procedures described in the following sections will be followed.

Groundwater sampling will be conducted by qualified Parsons ES scientists and technicians trained in the conduct of well sampling, records documentation, and chain-of-custody procedures. In addition, sampling personnel will have thoroughly reviewed the work plan and this site-specific sampling and analysis plan prior to sample acquisition and will have a copy of both available onsite for reference.

Activities that will occur during groundwater sampling are summarized below:

- Assembly and preparation of equipment and supplies;
- Inspection of the well integrity, including:
    - Protective cover, cap and lock,
    - External surface seal and pad,
    - Well stick-up, cap, and datum reference,
    - Internal surface seal,
    - Condition of any dedicated equipment, if present;
- Groundwater sampling, including:
    - Water-level measurements,
    - Visual inspection of borehole water,
    - Well casing evacuation,
    - Sampling;
- Sample preservation and shipment, including:
    - Sample preparation and preservation, as appropriate,
    - Onsite measurement of physical parameters,
    - Sample labeling,
    - Sample packaging in appropriate shipping containers;

- Completion of sampling records;
- Completion of chain-of-custody records; and
- Sample shipment via overnight courier.

Detailed groundwater sampling and sample handling procedures are presented in following sections.

4.1 Groundwater Sampling Locations

Groundwater samples will be collected from the 11 wells shown in Figure 10.1 of the RAP, using either a disposable bailer or a thoroughly decontaminated peristaltic pump with new, dedicated flexible tubing.

4.2 Preparation for Sampling

All equipment to be used for sampling will be assembled and properly cleaned and calibrated (if required) prior to the beginning of the sampling event. In addition, all recordkeeping materials will be gathered prior to leaving the office. A brief organizational meeting will be held to ensure proper communication between project management staff and field personnel.

4.3 Equipment Decontamination

All portions of sampling and test equipment that will contact the sample will be thoroughly cleaned before each use. This equipment may include Teflon® bailers, water-level probe and cable, oil/water interface probe and cable, test equipment for onsite use, and other equipment or portions thereof which will contact the samples. Based on the chemical constituents present at Area D, the following decontamination protocol will be used:

- Clean with potable water and phosphate-free laboratory detergent (Liquinox® or equivalent);
- Rinse with potable water;
- Rinse with distilled or deionized water;
- Rinse with reagent-grade isopropanol;
- Rinse with distilled or deionized water; and
- Air dry the equipment prior to use.

All decontamination fluids will be temporarily placed in 55-gallon D.O.T. approved containers. Final disposal will be determined based on laboratory analytical results. Water with COC concentrations below SDDENR groundwater quality standards will be discharged onto the ground surface near the source well. Water with contamination above state standards will be filtered through granular activated carbon (GAC), sampled, and then discharged to either the ground surface or the sanitary sewer. Ellsworth AFB will be responsible for the final disposition of all investigation-derived waste (IDW) generated as part of this project.

Any deviations from these procedures will be documented in the field scientist's field notebook and on the groundwater sampling form. If pre-cleaned dedicated sampling equipment is used, the decontamination protocol specified above will not be required. Laboratory-supplied sample containers will be cleaned and sealed by the laboratory and therefore will not need to be cleaned in the field. Equipment field blanks and equipment rinseate samples will be collected to assure that all containers and field equipment are free of contamination.

4.4 Equipment Calibration

As required, field analytical equipment will be calibrated according to the manufacturer's specifications prior to field use. This applies to equipment used for onsite chemical measurements such as pH, electrical conductivity, and temperature.

4.5 Sampling Procedures

Special care will be taken to prevent contamination of the groundwater and extracted samples. The two primary ways in which sample contamination can occur are through contact with improperly cleaned equipment and by cross-contamination through insufficient decontamination of equipment between wells. To prevent such contamination, the peristaltic pump and water level probe and cable used to determine static water levels and well total depth will be thoroughly cleaned before and after field use and between uses at different sampling locations according to the procedures presented in section 4.3. In addition to the use of properly cleaned equipment, a clean pair of new, disposable nitrile gloves will be worn each time a different well is sampled. New, clean tubing will be used for the peristaltic pump for each well sampled. Wells will be sampled sequentially from areas suspected to be least contaminated to areas suspected to be more contaminated. Plastic will be placed around each of the wells to be sampled and sampling equipment will not be allowed to come in contact with the ground surface at any time during the sampling event.

The following paragraphs present the procedures that comprise groundwater sample acquisition from all groundwater sampling locations. These activities will be performed in the same order as presented below. Exceptions to this procedure will be noted in the Parsons ES field scientist's field notebook.

4.5.1 Preparation of Location

Prior to starting the sampling procedure, the area around the well will be cleared of foreign materials, such as brush, rocks, and debris. These procedures will prevent sampling equipment from inadvertently contacting debris around the monitoring well. New, clean plastic (4 to 6 mil) we be placed around the well to prevent the contamination of both the ground surface and any equipment that may come into contact with the ground surface.

4.5.2 Water Level and Total Depth Measurements

Prior to removing any water from the well the static water level will be measured. An electrical water level probe will be used to measure the depth to groundwater below the datum to the nearest 0.01 foot. If the total depth of the well is not known or is suspected to be inaccurate, total well depth will be measured by slowly lowering the water level probe to the bottom of the well. Total well depth will be measured to the nearest 0.01 foot. Total depth will only be measured when absolutely necessary to minimize the amount of sediment disturbance in the well. Based on water level and total depth information, the volume of water to be purged from the well can be calculated.

4.5.3 Well Purging

The volume of water contained within the well casing at the time of sampling will be calculated, and three times the calculated volume will be removed from the well. Whenever practical, the purge rate will not exceed the recharge rate of the well to minimize groundwater draw down. This may not be possible in the slower recharging wells at the site. If a well is purged dry, it will be sampled as soon as enough groundwater to allow sampling reenters the well. Sample compositing, or sampling over a lengthy period by accumulating small volumes of water at different times to eventually obtain a sample of sufficient volume, will not be allowed. Care will also be taken to minimize the disturbance to the water column in the well. If a bailer is used, it will be lowered and removed from the water slowly. If a pump is used, the flow rate will be lowered to match the recharge rate of the well. The pH, temperature, dissolved oxygen, and specific conductivity will be monitored at the beginning of the purge and after each well volume. Purging will continue until these parameters have stabilized to within 10 percent among three consecutive readings. If a peristaltic pump is used for well purging, a flow cell may be used to take continuous measurements of the purge parameters. Purging should stop after all parameters have stabilized over a 5 minute period. All purge water will be placed in 55-gallon containers and disposed of as described in section 4.3. Disposable PVC or Teflon® bailers or a peristaltic pump with new tubing will be used for well evacuation.

4.5.4 Sample Extraction

Either disposable, polyethylene bailers or a peristaltic pump with new tubing for each well will be used to extract groundwater samples from the well. Bailers will be used only for those wells with known or suspected free product to minimize the potential for sampling equipment contamination. If depth to groundwater exceeds approximately 21 feet it will also be necessary to extract a sample using a bailer because of the vacuum lift limitations of a peristaltic pump. Both types of extraction equipment will be lowered into the water gently to prevent splashing and extracted gently to prevent creation of an excessive vacuum in the well. The sample will be transferred directly to the appropriate sample container. The water sample will be transferred from the bottom of the bailer using a bottom emptying device to allow a controlled flow into the sample container. Water from the peristaltic pump can be directly discharged into the sample container. The water should be carefully poured down the inner walls of the sample bottle to minimize aeration of the sample. Sample containers for VOC analysis will be filled at approximately 200 milliliters per minute (mL/min) and all other sample collection rates will not exceed 400 mL/min. Volatile samples will be collected first, followed by any other analytical samples. Samples for field parameter analysis will be collected last.

Unless other instructions are given by the analytical laboratory, sample containers will be completely filled so that no air space remains in the container. Excess water collected during sampling will be placed into the 55-gallon containers used for well purge waters and disposed of as described in section 4.3.

4.6 Onsite Chemical Parameter Measurement

Dissolved oxygen (DO) measurements will be taken onsite using a meter with a downhole oxygen sensor. The DO meter will be decontaminated, prior to each use, following decontamination procedures described in section 4.3. DO measurements will be taken immediately following groundwater sample acquisition. Where DO measurements will be taken in wells which have not been sampled, the well will be purged until DO measurements stabilize.

Because the pH, temperature, specific conductance, redox potential, and other chemical parameters of a groundwater sample can change significantly within a short time following sample acquisition, these parameters will be measured in the field in unfiltered, unpreserved, "fresh" water collected by the same technique as the samples taken for laboratory analyses. The measurements will be made in a clean, plastic, flow-through cell and the measured values will be recorded in the groundwater sampling record. Tables 10.1 and 10.2 in the body of the RAP lists the chemical analytical protocol for groundwater samples.

4.7 Sample Handling

This section describes the handling of samples from the time of sampling until the samples arrive at the laboratory.

4.7.1 Sample Container and Labels

Sample containers and appropriate container lids will be provided by the laboratory. The sample containers will be filled as described in section 4.5.4, and the container lids will be tightly closed. Container lids will not be removed at any time prior to sample collection. The sample label will be firmly attached to the container side, and the following information will be legibly and indelibly written on the label:

- Facility name;
- Sample identification;
- Sample type (groundwater, surface water, etc.);
- Sampling date;
- Sampling time;

- Preservatives added; and
- Sample collector's initials.

4.7.2 Sample Preservation

The laboratory will add any necessary chemical preservatives prior to shipping the containers to the site. Samples will be properly prepared for transportation to the laboratory by placing the samples in a cooler containing ice to maintain a shipping temperature of 4 degrees centigrade (°C).

4.7.3 Sample Shipment

After the samples are sealed and labeled, they will be packaged for transport to Evergreen Analytical, Inc. of Wheat Ridge, Colorado, the AFCEE-approved laboratory for this demonstration. Samples will be shipped priority overnight via Federal Express®. The following packaging and labeling procedures will be followed:

- Package sample so that it will not leak, spill, or vaporize from its container;
- Label shipping container with:
    - Sample collector's name, address, and telephone number;
    - Laboratory's name, address, and telephone number;
    - Description of sample;
    - Quantity of sample; and
    - Date of shipment.

The packaged samples will be delivered to the laboratory as soon as possible after sample acquisition.

4.7.4 Chain-of-Custody Control

After the samples have been collected, chain-of-custody procedures will be followed to establish a written record of sample handling and movement between the sampling site and the laboratory. Each shipping container will have a chain-of-custody form completed in triplicate by the sampling personnel. One copy of this form will be kept by the sampling contractor after sample delivery to the analytical laboratory, and the other two copies will be retained at the laboratory. One of the laboratory copies will become a part of the permanent record for the sample and will be returned with the sample analytical results. The chain-of-custody will contain the following information:

- Sample identification number;
- Sample collector's printed name and signature;

- Date and time of collection;
- Place and address of collection;
- Sample matrix;
- Chemical preservatives added;
- Analyses requested;
- Signatures of individuals involved in the chain of possession; and
- Inclusive dates of possession.

The original chain-of-custody documentation will be placed inside the shipping container so that it will be immediately apparent to the laboratory personnel receiving the container, but will not be damaged or lost during transport. The shipping container will be sealed with chain-of-custody labels so that it will be obvious if the seal has been tampered with or broken.

4.7.5 Sampling Records

In order to provide complete documentation of the sampling event, detailed records will be maintained by the Parsons ES field hydrogeologist. At a minimum, these records will include the following information:

- Sample location (facility name);
- Sample identification;
- Sample location map or detailed sketch;
- Date and time of sampling;
- Sampling method;
- Field observations of
  - Sample appearance,
  - Sample odor;
- Weather conditions;
- Water level prior to purging;
- Total well depth;
- Purge volume;
- Water level after purging;

- Well condition;
- Sampler's identification;
- Field measurements of pH, temperature, and specific conductivity; and
- Any other relevant information.

Groundwater sampling activities will be recorded on a groundwater sampling form. Figure 5 shows an example of the groundwater sampling record.

4.8 Laboratory Analyses

Laboratory analyses will be performed on all groundwater samples and the required QA/QC samples (see section 4.9). The analytical methods and detection limit requirements for this sampling event are listed in Tables 10.1 and 10.2 in the body of the RAP. Evergreen Analytical Laboratories of Wheat Ridge, CO, will be performing laboratory analytical analysis for the 1995 annual sampling event.

Prior to sampling, arrangements will be made with the laboratory to provide a sufficient number of appropriate sample containers for the samples to be collected. All containers, preservatives, and shipping requirements will be consistent with laboratory protocol.

Laboratory personnel will specify any additional QC samples and prepare bottles for all samples. For samples requiring chemical preservation, preservatives will be added to containers by the laboratory prior to shipping. Shipping containers, ice chests with adequate padding, and cooling media will be sent by the laboratory to the site. Sampling personnel will fill the sample containers and return the samples to the laboratory.

4.9 Quality Assurance/Quality Control Procedures and Sampling

Field QA/QC samples for groundwater sampling will include collection of field duplicates, equipment rinseate samples, and field and trip blanks. QA/QC procedures will include decontamination of the water level probe, use of analyte-appropriate containers, and chain-of-custody procedures for sample handling and tracking. All samples to be transferred to the analytical laboratory for analysis will be clearly labeled to indicate sample number, location, matrix (e.g., groundwater), and analyses requested. Samples will be preserved in accordance with the analytical methods to be used, and water sample containers will be packaged in coolers with ice to maintain a temperature of 4°C.

All field sampling activities will be recorded in a bound, sequentially paginated field notebook in permanent ink. All sample collection entries will include the date, time, sample locations and numbers, notations of field observations, and the sampler's name and signature.

Ground Water Sampling Record

SAMPLING LOCATION ____________
SAMPLING DATE(S)____________

GROUND WATER SAMPLING RECORD - MONITORING WELL ____________
(number)

REASON FOR SAMPLING: [ ] Regular Sampling; [ ] Special Sampling;
DATE AND TIME OF SAMPLING: ____________, 19___ ________ a.m./p.m.
SAMPLE COLLECTED BY: ________________ of ______________
WEATHER:____
DATUM FOR WATER DEPTH MEASUREMENT (Describe):______________
____
____

MONITORING WELL CONDITION:

[ ] LOCKED: [ ] UNLOCKED
WELL NUMBER (IS - IS NOT) APPARENT
STEEL CASING CONDITION IS:______________________________
INNER PVC CASING CONDITION IS:___________________________
WATER DEPTH MEASUREMENT DATUM (IS - IS NOT) APPARENT
[ ] DEFICIENCIES CORRECTED BY SAMPLE COLLECTOR
[ ] MONITORING WELL REQUIRED REPAIR (describe):____________
____
____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH______________
Items Cleaned (List):________________________________
____
____

2 [ ] WATER DEPTH ______________________FT. BELOW DATUM
Measured with:______________________________________

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Appearance:____
Odor:____
Other Comments:_____________________________________

4 [ ] WELL EVACUATION:
Method:____
Volume Removed:____________________________________
Observations: Water (slightly - very) cloudy
Water level (rose - fell - no change)
Water odors:_______________________________
Other comments:____________________________

Figure 5

Ground Water Sampling Record - Monitoring Well No. ______ (Cont'd) **Ground Water Sampling Record**

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: ______________________________
[ ] Pump, type: ______________________________
[ ] Other, describe: ______________________________
____

Sample obtained is [ ] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Temp: __________ • ______ Measured with: ______________
pH: ________________ Measured with: ______________
Conductivity: __________ Measured with: ______________
Other: ______________________________________
____

7 [ ] SAMPLE CONTAINERS (material, number, size): ______________
____
____
____

8 [ ] ON-SITE SAMPLE TREATMENT:

[ ] Filtration: Method ____________ Containers: ____________
Method ____________ Containers: ____________
Method ____________ Containers: ____________

[ ] Preservatives added:

Method ____________ Containers: ____________
Method ____________ Containers: ____________
Method ____________ Containers: ____________
Method ____________ Containers: ____________

9 [ ] CONTAINER HANDLING:

[ ] Container Sides Labeled
[ ] Container Lids Taped
[ ] Containers Placed in Ice Chest

10 [ ] OTHER COMMENTS: ______________________________
____
____
____
____

Figure 5 (Continued)

Groundwater QA/QC sampling frequency will be 10 percent or one sample for every ten wells sampled. In the event that less than ten wells will be sampled in an event, a minimum of one sample will be collected. This ten percent frequency also applies to equipment rinseate samples and field duplicates. One decontamination water sample and one field blank will be collected per sampling event. One trip blank will be sent with each sample shipment. The laboratory should plan to conduct one matrix spike analysis, one laboratory control sample, and one laboratory blank test for each specific analysis requested. A more comprehensive discussion of QA/QC requirements is presented in the QAPP (Appendix J).

5.0 FIELD QUALITY ASSURANCE/QUALITY CONTROL SAMPLES

As a check on field sampling, QA/QC samples, including trip blanks, field blanks, decontamination water blanks, equipment rinseate blanks, and field duplicates will be collected. Each type of QA/QC sample is described below.

5.1 Trip Blanks

A trip blank is defined as a sample bottle filled by the laboratory with analyte-free laboratory reagent-grade water, transported to the site, handled like a sample but not opened, and returned to the laboratory for analysis. One trip blank will accompany every cooler of environmental samples sent to the laboratory. Trip blanks are analyzed only for Method SW8020.

5.2 Decontamination Water Blank

A decontamination water blank is designed to check the purity of potable water used for equipment decontamination during the field operation. One decontamination water blank will be collected for each water source used during the field work. Decontamination water blanks are collected by filling the appropriate sample container directly from the potable water source. Decontamination water blanks are labeled, preserved, handled, and shipped in the same manner as an environmental water sample. The blank will be analyzed for the same analytes and parameters as the environmental samples.

5.3 Field Blanks

A field blank is designed to assess the effects of ambient field conditions on sample results. A field blank will consist of a sample of distilled water poured into a laboratory-supplied sample container while sampling activities are underway. The field blank will be analyzed for the same analytes and parameters as the environmental samples.

5.4 Equipment Rinseate Blanks

Equipment rinseate blanks will be collected from field equipment such as continuous core barrels. Equipment rinseate blanks are prepared by pouring distilled water over field equipment that has been decontaminated. The rinseate water is then collected, transferred to a sample bottle, and analyzed at the laboratory. The results of these sample analyses indicate how well the sampling equipment was decontaminated.

5.5 Field Duplicate Samples

A field duplicate is defined as two or more samples collected independently at the same sampling location during a single act of sampling. Soil samples are divided into two equal parts for analysis. Duplicates of water samples will be collected by filling additional sample containers at each duplicated sampling event.

Field duplicates will be indistinguishable from other samples by the laboratory. One complete sample set will be identified with a coded identifier, which will be in the same format as other identifiers used with this matrix. Both the coded and actual sample identifiers will be recorded in the field notebook. The coded identifier will be used on the chain-of-custody forms.

APPENDIX J

PROGRAM QUALITY ASSURANCE PROJECT PLAN

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SECTION 1

MANAGEMENT SYSTEMS

1.1 GENERAL

The Quality Assurance Program Plan (QAPP) for the field test of the risk-based approach for the remediation of eight sites has been prepared to present the organization, objectives, functional activities, and specific quality assurance (QA) and quality control (QC) activities associated with Parsons Engineering Science's (Parsons ES) work under Contract F41624-93-C-8044, "Risk-Based Approach to Fuel Spill Remediation." This multi-site initiative is sponsored by the Air Force Center for Environmental Excellence (AFCEE) at Brooks Air Force Base (AFB), Texas. This QAPP incorporates the criteria established by the American National Standards Institute/American Society for Environmental Programs (ANSI/ASQC E-4-1994), in *"Specifications and Guidelines for Quality Systems for Environmental Data Collection and Environmental Technology Programs,"* July 1994, (Draft) and the guidelines established by the US Environmental Protection Agency (EPA) in *"Risk Assessment Guidance for Superfund, Volume 1: Human Health Evaluation Manual"* [Parts A, B, and C] (EPA, 1989a, 1991a, and 1991b).

The eight AFCEE sites selected for remediation using the risk-based approach are as follows:

- Carswell AFB - ST-14A,
- Carswell AFB - ST-14B,
- Wurtsmith AFB - OT-42,
- Wurtsmith AFB - KC-135,
- Myrtle Beach AFB, - MOGAS Storage,
- Ellsworth AFB-Area D,
- Malmstrom AFB - Pumphouse #2, and
- Charleston AFB - ST-27.

This QAPP describes the specific sampling, sample handling and storage, custody, and field and laboratory measurement and analysis protocols which will be followed at the aforementioned sites. It also describes the incorporation of sampling results into a risk-based approach to determine the best remediation alternative for each of the eight sites.

The EPA requires that all environmental monitoring and measurement efforts mandated or supported by EPA participation include a centrally managed QA program (EPA, 1980). Any party generating data under such a program has the responsibility to implement minimum procedures to assure that the precision, accuracy, completeness, comparability, and representativeness of its data are known and documented. To ensure that this responsibility is met uniformly, each party must prepare a written QAPP covering each project it is to perform. This QAPP has been prepared to satisfy these requirements.

1.2 POLICY

This QAPP sets forth Parsons Engineering Science, Inc.'s commitment to quality in all activities, products, and services. This QAPP is designed to assure that projects and activities managed and conducted by Parsons ES are accomplished in an approved, prescribed manner by trained and competent staff.

Parsons ES management, assisted by the Quality Assurance (QA) staff, is responsible for achievement and documentation of product or service quality. The QA staff is charged with verifying the achievement of quality as well as providing assistance to the project organization in developing and implementing viable QA methods.

1.3 PURPOSE

This document establishes the QA requirements for Parsons ES and assigns responsibility for ensuring that project objectives will be achieved. It consists of the QA Program requirements which are responsive to ANSI/ASQC E4-1994(Draft).

1.4 SCOPE

The requirements of this document apply to Parsons ES and its laboratories. Quality requirements specified in this document are tailored to the needs of the AFCEE risk-based remediation demonstration program. Parsons ES-wide QA programs that supplement project-specific requirements are also briefly discussed.

1.5 ORGANIZATION AND RESPONSIBILITIES

Parsons ES is committed to performing quality work for our clients. This is accomplished as a company and as individuals by completely understanding the requirements to be met and meeting these requirements the first time. Quality is as important as cost and schedule, and therefore receives an equal amount of management attention and effort.

The primary responsibility for meeting the quality objectives of a project remains with the operational personnel. They will perform their work in accordance with the standards of their profession, accepted practices, and applicable regulations. In the absence of specific guidelines, they will follow best scientific or technical judgment.

Management will regularly assess and document the adequacy of the quality system. The management of Parsons ES defines the objectives of the assessment process and determines the measures for ensuring that the quality program has been established, documented, and implemented effectively. The Parsons ES QA/QC manager (John Giammona) will have primary responsibility for reviewing the field and analytical data, and for assuring that the work is performed in accordance with this QAPP.

To ensure that each of the eight remediation sites is managed using the Total Quality (TQ) Methodology, regularly scheduled briefings will be conducted with both regulatory and AFCEE personnel. These briefings will aid in defining project goals and scope as well as redefining objectives, as needed, and addressing current issues as the multi-site remediation project progresses. These meetings will allow for the coordination of field work, sampling and analysis, and feedback to Parsons ES regarding what risks are indicated by the data. The meetings will be an integral part of defining a site-specific risk-based approach.

The responsible officers for the QAPP implementation are as follows:

John Giammona -- QA/QC Manager
Doug Downey -- Project Manager
Leigh Benson -- Deputy Project Manager

1.6 QUALITY ASSURANCE PROGRAM

This QAPP is an integral part of the Parsons ES Quality Improvement Program (QIP). It constitutes a philosophy of and commitment to continuous improvement of Parsons ES products and services, and total satisfaction of internal and external customers. It is through Parsons ES employees, using teamwork, establishing measurable goals, and ensuring the attainment of these goals, that quality is achieved. This program has the endorsement of Parsons ES Responsible Managers who have the authority, responsibility, and accountability to establish management systems consistent with the requirements of this document and to ensure successful implementation.

Environmental compliance programs meet the applicable requirements of the Parsons ES QA Program. At a minimum, the environmental program controls apply to procurement, document/record control, sampling, analysis, data verification/validation, audits, inspections, calibration of equipment, nonconformance/ corrective action control, control of items and services, and training activities.

1.7 PLANNING

The Parsons ES QA program establishes a systematic planning process to:

- Identify the customer(s), their needs, and their expectations of the work to be performed;
- Identify the technical and quality goals required to meet the needs and expectations of the customer;

- Translate the technical and quality goals into specifications that will produce the desired result;
- Consider any cost and schedule constraints within which project activities are required to be performed; and
- Identify acceptance criteria by which the results will be evaluated and customer satisfaction will be determined.

The development of a QA plan represents Parsons ES's decision to carry out a specific project, and represents the detailed and systematic examination of all factors involved in the performance of a project. The size and scope of a project determine the complexity of a plan. However, no matter what the project size or scope, a good plan:

- Is based on facts and valid assumptions;
- Provides for the necessary organization and assigns responsibilities;
- Delegates authority consistent with control and/or responsibility;
- Provides for the use of existing resources;
- Provides for personnel, material, training, etc.;
- Is simple;
- Is flexible;
- Provides for contingencies;
- Is coordinated;
- Provides for control (lines of communication); and
- Provides for successful completion of the project.

1.8 WORK PROCESSES

1.8.1 Process Control

The Parsons ES QA Program promotes the concept that quality is integrated into work processes through each employee who has been properly trained, motivated, and empowered and who is knowledgeable of the procedures, instructions, drawings, specifications, and other related administrative and technical documents that control the work. Work process control is applicable to engineering, procurement, material control, installation, modification, construction, maintenance, operations, testing, inspection, hazardous waste management and transportation, environmental characterization and restoration, document control and management, and research and development. Processes are fully integrated with the federal, state, industry, and client requirements.

1.8.2 Work Procedures/Instructions

The Project Manager (Doug Downey) ensures that activities that affect quality are planned, authorized, prescribed, and accomplished by clear and concise management systems. The degree to which procedures are detailed and used is based on the importance of the item, activity, or service to the environment, public, safety, cost, or schedule. Activities identified in this QA Program will be incorporated in approved procedures as appropriate.

Procedures will be developed, reviewed, approved, and validated by qualified personnel and designated as controlled documents before release for use. All Parsons ES personnel are responsible for complying with approved work process procedures and instructions.

1.9 PERSONNEL TRAINING AND QUALIFICATIONS

Personnel involved in activities affecting the quality of operations will be trained and, where applicable, certified to perform assigned duties.

Development of training programs and conduct of training are the responsibilities of line management. Training programs are conducted according to appropriate training policies and are designed so that the employee:

- Possesses adequate knowledge of the processes and procedures needed to conduct the assigned tasks;
- Has a working knowledge of the tools required;
- Has an understanding of acceptance and rejection criteria of the work process, systems terminology, and reasons for specific controls so that process variability is maintained at a minimum;
- Has an acceptable understanding of the safety conditions of the work tasks;
- Knows the consequences of inadequate quality attainment; and
- Is provided training for continued maintenance of job proficiency and process improvement.

Training procedures establish requirements for the conduct of training and maintenance of training records. Training is conducted by qualified and knowledgeable instructors. Personnel performing work requiring special skills are trained and qualified before performing the work. Proficiency is demonstrated by testing, on-the-job demonstration, or classroom attendance as determined by the Project Manager, instructor, or the requirements of established standards or regulations. Continued proficiency is evaluated, maintained, and documented. Management development programs provide training to enhance the development of professional skills in management, interpersonal relationships, and communications.

1.10 PROCUREMENT OF ITEMS AND SERVICES

The Parsons ES QA Program establishes a procurement process designed to ensure that procured items and services comply with documented requirements and that they perform acceptably in service.

Procurement technical specifications are reviewed and approved to ensure the inclusion of applicable codes, standards, tests, acceptance standards, quality requirements, and the identification of records to be maintained or submitted.

Procurement and engineering procedures establish requirements to ensure that the appropriate elements of the Quality Program have been incorporated into procurement documents, based on the level of quality associated with the procured item or service.

Commercial-grade item procurement documents incorporate requirements to ensure that identified critical characteristics have been satisfied. Changes to technical specifications receive the same review and approval as the original document.

The process of tagging and segregating materials provides assurance that only acceptable items are issued for use. Before releasing an item for critical installation or use, documentation is available to support the acceptance of the item based on compliance with the required technical requirements, testing, documentation, and closure of all applicable nonconforming conditions.

Significant items of nonconformance identified with supplier-furnished items or services, whether known or unknown by the supplier, are processed according to the actions and responsibilities necessary to control the procurement of items and services.

1.11 RECORDS

The Parsons ES QA Program requires that the scope of the quality records and project records to be retained are identified within QA plans. These records, at a minimum, apply to design, procurement, receipt inspection, assessments, deficiency documents, material control, installation, maintenance, testing, modifications, operations, environmental monitoring, and hazardous waste management and transportation. Special procedural controls document the generation, collection, maintenance, and control of safeguarded records. Procedures establish controls for the physical protection, preservation, traceability, and retrievability of records.

Project records generated under this program to be retained by Parsons ES shall be maintained in a central, dedicated file system. Quality and project records to be retained by laboratories shall be maintained according to requirements specified by Parsons ES in subcontract documents.

1.12 COMPUTER HARDWARE AND SOFTWARE

Computer hardware and software configurations include, but are not limited to:

- Experimental design,
- Design analysis,
- Modeling of environmental processes and conditions,
- Operation or process control of environmental technology systems, and
- Data bases containing environmental data.

1.12.1 Testing

The Parsons ES QA program requires that computer hardware and software configurations are tested prior to actual use, and that the results are documented and maintained. Changes to hardware and software configurations are assessed to determine the impact of the change on the technical and quality objectives of the projects; appropriate actions are then taken.

1.12.2 Software Requirements

The Parsons ES QA program ensures that computer software meets user requirements and conforms to all applicable consensus standards, or data management criteria. The Program Manager or designee establishes acceptance criteria for the use of commercially acquired software and program documentation. Reference guides and user manuals will be easily accessible to users.

Software developed specifically for the project will be developed using an approved software development methodology that considers the complete life-cycle aspects of the software. User-developed programs are independently validated, verified, and documented according to the intended use of the software. Changes to user-developed software will be assessed to determine the potential impact of the change on the performance of the software, and appropriate actions are then taken.

1.13 MEASURING AND TEST EQUIPMENT

The Parsons ES QA Program for control of Measuring and Test Equipment (M&TE) has been established to ensure that the selected M&TE is the proper type, range, accuracy, and tolerance for the intended use. Tools, gauges, instruments, and other M&TE used for activities affecting data quality (such as sampling, data gathering, fabrication, and construction) will be calibrated at specified periods to maintain accuracy within specified limits.

Equipment found to be unsatisfactory for the prescribed use will be recalibrated and certified within tolerance before being used again. The validity of measurements, analyses, and tests performed with out-of-calibration equipment will be evaluated, and such measurements and tests will be repeated, as required, using calibrated equipment. Out-of-calibration equipment or devices will be tagged or segregated and withheld from use until they have been recalibrated. If any equipment is consistently out of calibration, it will be repaired or replaced. Additional calibration will be performed whenever the accuracy of the equipment is suspect. Calibration and control measures are not required for standard commercial devices such as rulers, tape measures, or levels.

Calibrations will be conducted using certified equipment and/or standards with known valid relationships to nationally recognized performance standards. If no such nationally recognized standards exist, the alternative basis for the calibration will be documented. Documentation of calibration for all tools, gauges, and instruments will be maintained and will be traceable to the item.

1.14 ASSESSMENT AND RESPONSE

1.14.1 Management Assessments

Parsons ES management is committed assessing the success or lack of success in realizing office, division, or department objectives. The assessments are conducted by evaluating the performance of the QIP teams and the effectiveness of the TQM program, in addition to evaluating QA Status Reports, audit reports, surveillance reports, and corrective action status reports. At a minimum, activities are assessed to ensure that:

- The mission goals and objectives are clearly identified, communicated, and understood by those responsible for mission success;
- The requirements for internal and external customer satisfaction are understood and work processes for continuous improvements are routinely evaluated;
- The empowerment and training of employees is emphasized so that the effective use of resources to maximize quality and reduce process variability and costs is a part of the management system;
- Evaluations of trend analyses, lessons learned, performance indicator results, and other information gathered from the quality improvement program are analyzed and improvements are initiated as required;
- Required management systems are in place and effective in achieving mission objectives according to quality, environmental, and safety expectations; and
- focus is being given to methods of obtaining continuous improvement in the quality system and identifying barriers to achieving established missions and objectives.

Management has the responsibility and will be directly involved in conducting assessments, evaluating assessment results, ensuring effective problem evaluations, and taking corrective action. Senior managers routinely monitor the assessment activities of their subordinate managers and supervisors and conduct reviews to determine the reasons for success or failure in the achievement of objectives. Management assessments will be conducted by individuals with the necessary technical skills required to make effective conclusions about system performance. Line managers and supervisors have the responsibility to "walk their spaces" and personally take part in monitoring and assessing activities.

1.14.2 Independent Assessment

The Parsons ES QA Program provides for the development and implementation of a documented program by which independent audits, surveillances, and other assessments are conducted of all projects and departments, with emphasis on quality improvement.

Audits, surveillances, and other assessments are scheduled in a coordinated manner. The schedule is based on corporate, client, and regulatory requirements; trend data of an activity; complexity of an activity; history of compliance; and importance to safety and associated consequences as related to the public, employees, and the environment. Audit schedules are prepared with sufficient flexibility to permit unscheduled audits to take place for activities of questionable performance.

The audit program documents audit planning, qualification of audit personnel, audit performance, reporting, problem identification, corrective action, follow-up, and maintenance of audit records. Audit planning and the audit criteria place emphasis not only on compliance, but also on ensuring that performance excellence has been accomplished through work processes. Audits are conducted to measure conformance to established practices. Audits are accomplished by monitoring actual work performance, evaluating if work practices and procedures are adequate and conducive to an acceptable end product; identifying substandard practices; and providing recommendations for improvement. Audits are used as a management tool to verify the implementation and adequacy of the approved management systems in place.

Audits are conducted with a no-fault attitude toward identifying problems and in a spirit of helping to achieve excellence through problem identification and corrective action. The audit plan is directed toward the requirements of the documented quality program and not toward subjective interpretation of codes and standards. The audit process provides for reporting observations in addition to audit findings. Observations identify areas that merit improvement and do not require a response from the managers of the organizations being evaluated.

Results of audits, surveillances, and assessments are reviewed with the management of the evaluated organization at the completion of the activity, and followed up with a documented report. Findings identified during an audit or surveillance are formally tracked to closure. Unacceptable findings or untimely responses are escalated to the management level necessary to obtain satisfactory corrective action.

Management response to an audit finding must:

- Determine extent of reported condition;

- Determine root cause;
- Identify corrective action;
- Implement action to prevent recurrence;
- If appropriate, enter corrective actions into program/project lessons learned; and control the corrective action in accordance with existing QA and QIP procedures.

Technically qualified personnel validate the response to audit findings and verify the acceptability of the responses on a selected basis.

Personnel performing independent assessments are technically knowledgeable and focus on improving the quality of the process being assessed. They do not have direct responsibility in the assessment area of work.

1.15 QUALITY IMPROVEMENT

All Parsons ES employees are trained in TQM processes through the QIP. The Parsons ES QIP endorses and promotes a no-fault environment in which all personnel have the freedom and are expected to identify nonconforming items, activities, and procedures without fear of reprisal or recrimination. Personnel are encouraged to identify and communicate methodologies for improving quality and restricting process methods that would lead to unacceptable performance.

Items, processes, and services that do not meet established criteria and/or predetermined quality requirements are identified and documented, analyzed, disposed of, corrected, and validated. Causal factors are evaluated to establish a root cause condition, based on the importance to safety and the significance of the identified problem.

Responsible Managers provide senior managers with routine reports that document the results of analyses made of quality improvement data. The reports may address results of trend analyses, lessons learned, performance indicator evaluations, precursors to possible problems, corrective actions proposed, and any perceived barriers to improvement. Responsible managers ensure that resources are available to provide for timely resolution and correction of identified problems. When deposition cannot be resolved, the problem is escalated to a higher level of management for resolution and the process is documented.

Nonconforming items and activities are identified and controlled to prevent inadvertent installation, testing, or use. Any use-as-is dispositions of nonconforming items receive a documented justification by the organization that conducted the original review or by a designated qualified organization. Repaired, reworked, or replacement items are installed and tested according to the original requirements or technically designated alternatives.

Personnel who analyze or dispose of nonconforming items and activities are technically qualified and have pertinent background data available for their information and use.

SECTION 2

SAMPLING AND LABORATORY QUALITY ASSURANCE

2.1 PLANNING AND SCOPING

The generation, acquisition, and use of environmental data will be planned and documented. The type and quality of environmental data needed are identified using a systematic planning process related to the intended use of the data. Project-specific planning involves key users and customers of the data, as well as the technical staff responsible for obtaining, analyzing, and evaluating the data. Results of planning activities are subject to review for conformance to technical and quality expectations.

2.2 GOALS FOR SAMPLING AND LABORATORY QA

The overall or project precision of measurement data is a mixture of sampling and analytical factors. Analytical precision is much easier to control and quantify than sampling precision. Accuracy measures the bias in a measurement system and is difficult to measure for the entire data collection activity. Sources of error are the sampling process, field contamination, preservation, handling, sample matrix, sample preparation, and analytical techniques. Sampling accuracy may be assessed by evaluating results of field/trip blanks; analytical accuracy may be assessed through use of known and unknown QC samples and matrix spikes.

2.3 SAMPLING PROCEDURES

2.3.1 Sampling Protocols

Detailed sampling protocols will be provided on a site-by-site basis depending on the data required to support a risk-based remediation. Appendix H of each EE/CA, RAP, or CMS will include a brief description of the sampling protocols for each of the media of interest - soil gas, soil flux, soil, ground water, and surface water, as appropriate.

2.3.2 Field Operations

Field operations include field sampling procedures, QC sample collection, sample handling, sample custody, and sample analyses summaries. A detailed discussion of the procedures used to document, establish, and maintain custody of field samples is presented in each EE/CA, RAP, or CMS prepared under this program. Additionally, these requirements are set forth in the laboratory subcontract document. Parsons ES sampling personnel must complete all proper forms and documents for each sample taken. After collection, containerization, and documentation, samples will be maintained under the custody of field team members until relinquished to the overnight courier service. The sample shipment container will not be unsealed until the laboratory receives custody and breaks the sample seal.

2.4 EXISTING DATA REVIEW

Existing site-specific data will be used initially to describe the physical characteristics of environmental media and the nature and extent of contamination at each of the eight sites. Review of available site data will aid in defining additional site characterization data necessary to fill existing data gaps, support quantitative modeling efforts, develop long-term risk-based cleanup levels, and evaluate, select, and implement the most cost-effective remedial alternative for the site.

2.4.1 Site Background

A detailed description of site background is necessary to support additional site characterization needs and to quantitatively evaluate remedial options. Site-specific information to be included is geographic site location and corresponding map, historical and present site use, known petroleum-based product usage and storage areas, and information regarding when contamination was first detected at the site. Any prior site investigation work relevant to this remediation project will also be solicited and incorporated as appropriate.

2.4.2 Physical Setting

Data from previous site characterization efforts will be collected and used to define the physical setting at each site. Both site topography and surface hydrology data will be reviewed and used as necessary. Historical flow rates from nearby/impacted waterways, surface water, and surface elevation ranges will be noted. In addition, surficial soil permeability will also be included to aid in determining the risk of contaminant transport/migration in this surficial medium for health-based risk calculations.

Site geology and hydrogeology data generated from previous investigations will also be collected to aid in the overall determination of the fate and transport of the contaminants in a known geological stratum. Historical flow rates and direction of water flow will be included to aid in defining potential contaminant pathways which may pose a threat to human health and the environment. Maps of the approximate ground water surface will be included as visual aids.

Any information which may contribute to a preliminary determination of the nature and extent of contamination will be included. Soil gas data, soil data, surface water data, and ground water data will be used to determine the probable extent of contamination. In addition, findings of free-phase product will also be denoted. The aforementioned sampling information will be mapped out on a site-specific map noting both depths and concentrations of contaminants found to date and any suspected plumes of contaminants in the subsurface region. This information is critical to defining additional data needs.

2.5 DESIGN OF DATA COLLECTION OPERATIONS

This program consists of field tests of an innovative approach to remediation. Therefore, specific data will be necessary to supplement any existing data. Data collection is an important component of this effort. The design of data collection operations are defined, controlled, verified, and documented. The design process provides specifications for:

- Sample types, numbers, quantities, and sampling location requirements;
- Selection of testing methodology, including specific analytical instrumentation requirements;
- Requirements for field laboratory QA/QC activities;
- Sample handling, packaging, shipping, and custody requirements;
- Selection of analytical methods and quality performance expectations;
- Requirements and qualifications for sampling and analysis personnel;
- Selection of analytical facilities;
- Requirements for calibration and performance evaluation samples for analytical methods used;
- Assessments needed during the project;
- Data validation and verification methods;
- Techniques for assessing limitations on data use;
- Data reporting requirements;
- Waste disposal or minimization procedures; and
- Requirements for data security and archival.

Design of environmental and waste characterization data collection operations uses consensus-accepted experimental design techniques where possible, including the use of statistics. Key variables that determine or directly affect the quality of the results are identified and controlled, as appropriate, according to the design specifications.

2.5.1 Data Handling Methods

The data collection design process ensures that data are traceable to the procedures used to generate the data. Data transfer, reduction, verification, analysis and interpretation methods, and validation requirements will be determined and documented. Restrictions on the use of any interim results will be identified and stated with the data in a manner that clearly defines the nature of the restriction and the specific data to which it applies.

2.5.2 Design Documents

Results of the design process are documented in the project-specific EE/CA, RAP, or CMS. Included are work plans, sampling and analysis plans, field sampling plans, instruction guides, standard operating procedures, and operating manuals. Changes to data collection designs or procedures, including field changes, are subject to the same review and approval protocols as the original documents.

2.6 IMPLEMENTATION OF PLANNED OPERATIONS

The environmental data operations are implemented to ensure that the type and quality of environmental data required and expected will be obtained. Deviations from the plan will be documented and reported to management.

Data management, including transmittal, storage, validation, assessment, processing, and retrieval, will be performed in accordance with approved instructions, methods, and procedures.

2.6.1 Field Quality Assurance/Quality Control Samples

As a check on field sampling, QA/QC samples, including trip blanks, field blanks, decontamination water blanks, equipment rinseate blanks, and field duplicates will be collected. Each type of QA/QC sample is described below.

2.6.1.1 Trip Blanks

A trip blank is defined as a sample bottle filled by the laboratory with analyte-free laboratory reagent-grade water, transported to the site, handled like a sample but not opened, and returned to the laboratory for analysis. One trip blank will accompany every cooler of ground water, surface water, and soil samples sent to the laboratory. Trip blanks are analyzed only for Method SW8020.

2.6.1.2 Decontamination Water Blank

A decontamination water blank is designed to check the purity of potable water used for equipment decontamination during the field operation. One decontamination water blank will be collected for each water source used during the field work. Decontamination water blanks are collected by filling the appropriate sample container directly from the potable water source. Decontamination water blanks are labeled, preserved, handled, and shipped in the same manner as an environmental water sample. The blank will be analyzed for the same analytes and parameters as the environmental samples.

2.6.1.3 Field Blanks

A field blank is designed to assess the effects of ambient field conditions on sample results. A field blank will consist of a sample of distilled water poured into a laboratory-supplied sample container while sampling activities are underway. The field blank will be analyzed for the same analytes and parameters as the environmental samples.

2.6.1.4 Equipment Rinseate Blanks

Equipment rinseate blanks will be collected from field equipment such as continuous core barrels and bailers. Equipment rinseate blanks are prepared by pouring distilled water over field equipment that has been decontaminated. The rinseate water is then collected, transferred to a sample bottle, and analyzed at the laboratory. The results of these sample analyses indicate how well the sampling equipment was decontaminated.

2.6.1.5 Field Duplicate Samples

A field duplicate is defined as two or more samples collected independently at the same sampling location during a single act of sampling. Soil samples are mixed and divided into two equal parts for analysis. Duplicates of water samples will be collected by filling additional sample containers at each duplicated sampling event.

In some instances, field duplicates will be indistinguishable from other samples by the laboratory. One complete sample set will be identified with a coded identifier, which will be in the same format as other identifiers used with this matrix. Both the coded and actual sample identifiers will be recorded in the field notebook. The coded identifier will be used on the chain-of-custody forms.

2.6.2 Sample Control

Handling, storage, cleaning, packaging, shipping, and preservation of field and laboratory samples are detailed in Section 2.9 of this QAPP and will be performed according to the required specifications, protocols, or procedures to prevent damage, loss, deterioration, artifacts, or interference. Sample chain-of-custody will be tracked and documented.

Inspections and acceptance testing of sampling, measurement, and analytical instrumentation or other measurement systems and their components will be performed to confirm that the items conform to the specified design.

Final acceptance will be performed by independent personnel. When acceptance criteria are not met, deficiencies are resolved and re-inspection will be performed as necessary.

2.7 DATA QUALITY OBJECTIVES

The objective of these field tests is to determine the three-dimensional distribution of fuel hydrocarbon contamination at a site, to obtain the additional data needed to evaluate the effectiveness of specific remedial technologies including bioventing and intrinsic remediation to establish site-specific remediation goals that minimize or eliminate risks, and to implement the approved remedial design. This QAPP has been developed for use in conjunction with the sampling activities at United States Air Force bases and describes the QA/QC procedures and protocols that will be used during sample analysis. The QAPP will serve as a controlling mechanism during these investigations to ensure that a sufficient quantity of data is collected and that all data collected are valid, reliable, and defensible.

2.7.1 Analytical Data Quality Levels

Analytical data quality is specified in terms of levels defined in the data quality objectives (DQOs) guidance document (EPA, 1987a). Five analytical levels are defined:

Level I - Field screening using portable instruments, such as photoionization detectors. Results are often not compound-specific and not quantitative, but results are available in real-time. It is the least costly of the analytical options.

Level II - Field analyses using more sophisticated portable analytical instruments, such as a portable gas chromatograph (GC). In some cases, the instruments may be set up in an onsite mobile laboratory. A wide range in the quality of data may be attained, depending on the use of suitable calibration standards, reference materials, sample preparation equipment, and training of the operator. Results are available in real-time or within several hours.

Level III - Analyses performed in offsite laboratories. The laboratories may or may not use EPA Contract Laboratory Program (CLP) procedures, but do not usually use the stringent validation and documentation procedures required of CLP Level IV analyses.

Level IV - Analyses performed in offsite laboratories according to CLP protocols, which require stringent QA/QC procedures, documentation, and data validation.

Level V - Analyses by nonstandard methods performed in an offsite analytical laboratory.

For the risk-based remediation program, the following analytical levels will be used as indicated:

- Level I analytical methods will be used for air screening in worker breathing zones for health and safety purposes. Level I may also be used to screen samples to select portions for further analysis. For example, soil sample headspace may be screened to determine if laboratory analyses are required.
- Level II analyses will be used to determine the presence of compounds supporting the intrinsic remediation option for ground water. These data will be used to evaluate the effectiveness of intrinsic remediation at the site.
- Level III analyses will be used to satisfy the requirements for site characterization, risk analysis, decision document preparation, and site cleanup prioritization. Level III data from previous site investigations will be combined with newly acquired data to evaluate the magnitude and extent of contamination at certain sites. Level III data acquired during this investigation will be used to evaluate remedial alternatives.

- Level IV analyses will not be required.
- Level V analyses will not be required.

An effective QA program addresses quality objectives for both sampling and laboratory methodologies. Parsons ES field QA efforts are aimed primarily at assuring that samples are representative of the conditions in the various environmental media at the time of sampling. Laboratory QA efforts are aimed primarily at assuring that analytical procedures provide sufficient accuracy and precision to quantify contaminant levels in environmental samples. The laboratory will also ensure that analyzed portions are representative of each sample, and that the results obtained from analysis of each sample are comparable to those obtained from analysis of other similar samples.

2.7.2 Concentrations of Concern

In order to define data needs, potential concentrations of concern must be established. The *Guidance for Data Usability in Risk Assessments* (EPA, 1992) specifies that, to the extent possible, the analytical detection limit for a contaminant of concern should be no greater than 20 percent of the concentration of concern (e.g., risk-based criterion). The method detection limits (MDLs) to be used during this project have been chosen such that both nondetects and detects will be usable to the fullest extent possible for the risk assessment process to be followed.

2.7.3 Project Quality Assurance Objectives

The QA/QC program will provide the basic guidelines for evaluating analytical results for each site. Data quality assessments will be used to identify accurate and precise data that may be used to establish remediation quals and evaluate alternatives for each site. QA/QC is ensured through appropriate sample collection, preservation, and transport methods combined with an evaluation of laboratory analytical performance through the analysis of QC samples.

When analytical data fail to meet the required QA objectives, the technical report will discuss why the objectives were not met. Two major categories of non-compliance with QC requirements need to be considered:

- Requirements that are fully under a laboratory's control; and
- Requirements limited by the nature of the sample matrix.

Corrective action for noncompliance with QC standards that are fully under a laboratory's control (e.g., laboratory blanks, calibration standards, tuning, and laboratory check or control samples) will be addressed with a thorough reevaluation of the system and all calculations and, where practical, reanalysis of noncompliant samples. Corrective action for noncompliance with QC standards that is limited by the nature of the sample matrix (e.g., field blanks, matrix spikes, and duplicates) will be addressed with a thorough check of the system and all calculations, and the attachment of appropriate data qualifiers to noncompliant data.

2.8 DEFINITION OF CRITERIA

The data assessment criteria measure the quality of both the field and laboratory performance for the entire project and are expressed in terms of analytical accuracy, precision, completeness, comparability, representativeness, holding times, and detection limits. These criteria are described in the following subsections.

2.8.1 Accuracy

Accuracy is a measure of the closeness of a reported concentration to the true value. Accuracy is usually expressed as a bias (high or low) and is determined by calculating percent recovery (PR) from spiked samples. The level of recovery of an analyte and the resulting degree of accuracy expected for the analysis of QA samples and spiked samples are dependent upon the sample matrix, method of analysis, and the contaminant. The concentration of the analyte relative to the detection limit of the method is also a major factor in determining the accuracy of the measurement.

During field sampling and sample shipping, contamination may be introduced to the samples that could affect the accuracy of analysis results. Field and trip blanks will be used during sample collection and shipment to detect possible field contamination. Contamination affecting accuracy can also be introduced during laboratory analysis. Method blanks will be used during laboratory procedures to assess laboratory-introduced contamination.

Because accuracy information is critical when results are reported at or near a concentration of concern, the appropriate number of field blanks, trip blanks, and method blanks will be collected at each site to ensure that accurate information can be obtained.

Field spiking of environmental samples will not occur. Laboratory spiking methods are expected to be completed under more controlled conditions, and should therefore provide more reliable data than that which could reasonably be implemented in the field. However, field measurements for parameters such as pH and parameters involving colorimetric analyses will be assessed for accuracy in the field. Specifically, field instruments will be assessed for accuracy by the response to a known sample (such as a calibration standard). The objective for accuracy of field measurements is to achieve and maintain factory equipment specifications for the field equipment.

2.8.2 Precision

Precision is a quantitative measure of the variability of a set of measurements compared to the mean. It is usually reported as a coefficient of variation or a standard deviation of the arithmetic mean. Analytical results for QC samples are used to calculate the precision of the measurement process. During collection of samples, precision can be affected by the spatial variability of pollutant concentrations. Collection of adequate field duplicate samples will enable a determination of variability due to sampling and laboratory analysis practices. Analytical variability can be measured by analysis of laboratory duplicates and/or performance evaluation samples. Standard deviations and coefficients of variation can be used to determine the confidence level of data reported near a concentration of concern. Precision will be expressed in terms of the standard deviation or the relative percent difference (RPD) between the values resulting from duplicate analyses.

Because the concentration of analytes may be below detection limits in many environmental samples, RPD data will be generated by preparing matrix spikes in duplicate. The precision of the analytical method will thus be measured by calculating the RPD between the duplicate spikes, rather than environmental samples. Acceptable levels of precision will vary according to the sample matrix, the specific analytical method, and the analytical concentration relative to the method detection limit. For field duplicate samples, the target RPDs are 20 percent for water samples, 50 percent for soil samples, and 35 percent for soil gas samples.

At each site, adequate numbers of field and laboratory duplicates will be analyzed to allow for accurate calculations of the precision of analytical results. At a minimum, one field duplicate will be collected for every 10 environmental samples (i.e., frequency of 10 percent).

2.8.3 Completeness

Completeness is defined as the percentage of measurements, either field or laboratory, which are judged to be valid measurements on a method-by-method basis. Valid data will be defined as all data and/or qualified data considered to meet the DQOs for this project. Data completeness is expressed as percent complete (PC) and should not be less than 90 percent. At the end of each sampling event, the completeness of the data will be assessed. If any data omissions are apparent, the parameter in question will be resampled and/or reanalyzed, if feasible. Laboratory results will be monitored as they become available to assess laboratory performance and its effect on data completeness requirements. When appropriate, additional samples will be collected to ensure that laboratory performance meets PC requirements.

2.8.4 Comparability

Comparability expresses the confidence with which data from a sample, sampling round, site, laboratory, or project can be compared to those from another. Comparability during sampling involves sampling program design and time periods. Comparability during analysis involves analytical methods, detection limits, laboratories, units of measure, and sample preparation procedures. The objective for comparability is determined on a qualitative rather than quantitative basis. For this project, comparability of all data collected will be ensured by adherence to standard sample collection procedures, standard field measurement procedures, and standard reporting methods including consistent units.

In developing site-specific sampling plans, previous studies have been reviewed. Past designs have been incorporated whenever possible and appropriate to improve comparability as well as to build upon existing information about the site. For example, previously collected information about soil horizon stratification and depth to contamination will be used in selecting soil sampling depths. Data that are not comparable between studies will not be used quantitatively in this program.

2.8.5 Representativeness

Representativeness expresses the extent to which collected data define site contamination. Where appropriate, sample results will be statistically characterized to determine the degree to which the data accurately and precisely represent a characteristic of a population, parameter variation at a sampling point, process, or environmental condition. The data will be tested against the normal distribution when 30 or more samples are available for testing. A nonparametric test will be used when fewer than 30 samples are available.

Sampling selection, handling, and analytical procedures will strive to obtain the most representative sample possible. Sample handling and analytical procedures also incorporate consideration of obtaining the most representative sample possible. Representative samples will be achieved by the following:

- Collection of samples from a location(s) fully representing site conditions;
- Use of appropriate sampling methodology and equipment;
- Use of appropriate sampling procedures, including equipment decontamination;
- Use of appropriate analytical methodologies for the required parameters and detection limits; and
- Analysis of samples within the required holding times.

Sample representativeness is also affected by which portion of each collected sample is chosen for analysis. The laboratory will adequately homogenize all samples prior to taking aliquots for analysis to ensure that the reported results are representative of the sample received. Because many homogenization techniques may contaminate the sample, or cause loss of contaminants through volatilization, homogenization will be avoided or modified in some cases to minimize these risks.

2.9 LABORATORY SAMPLE HANDLING

2.9.1 Sample Custody

Sample custody is critical to ensuring the integrity of field sampling and laboratory analysis. Parsons ES's project task manager or quality assurance (QA) officer will notify the laboratory project coordinator of anticipated field sampling activities and the subsequent transfer of samples to the laboratory. This notification will include information concerning the number and type of samples to be shipped as well as the anticipated date of arrival. All sample shipments to the laboratory will be accompanied by chain-of-custody (COC) forms which are to be completed by the laboratory. Copies of the completed COC records for the appropriate samples will be transmitted to Parsons

ES upon receipt of samples. One copy of the COC form will be maintained by the laboratory. The original COC will be returned to Parsons ES with the report package.

2.9.2 Sample Handling

The types of sample containers, sample volumes, methods of preservation, and holding times for each sample matrix by analytical method will be defined by Parsons ES prior to mobilization to the field. Parsons ES field team members will ship samples daily upon sample collection, normally Monday through Friday, to enable the laboratory to analyze the samples within the specified holding times. The laboratory will provide clean containers for each type of analysis, including preservatives, where appropriate. The laboratory will provide documentation attesting to the cleanliness of the containers. The laboratory will also document and guarantee the purity of any reagents supplied as preservatives.

To facilitate sample preparation and analysis within the specified holding times, the laboratory will track the progress of sample preparation, analysis, and report preparation. Samples received by the laboratory will be checked carefully for label identification, COC, and any discrepancies. The laboratory will also note physical damage, air bubbles in samples of volatile organic compounds (VOCs), incomplete sample labels, incomplete paperwork, discrepancies between sample labels and paperwork, broken or leaking containers, and inappropriate caps or bottles. The temperature and pH of samples will be determined and recorded as appropriate. The laboratory project coordinator will designate the samples to be included in each analytical batch consistent with the applicable holding time restrictions.

Laboratory sample custody will be maintained by the following procedure:

- The laboratory will designate a sample custodian responsible for maintaining custody of the samples and all associated paperwork documenting that custody.
- Upon receipt of the samples, the sample custodian will sign the original COC form and compare the analyses requested thereon with the tag on each sample container.
- A qualitative assessment of each sample container will be performed to note any anomalies such as broken or leaking bottles, or lack of preservation (e.g., ice melted enroute). This assessment will be recorded as part of the incoming COC procedure.
- If all data and samples are correct, and there has been no tampering with the custody seals, the "received by laboratory" box on the COC form will be signed and dated.
- Care will be exercised to document any labeling or descriptive errors. In the event of discrepant documentation, breakage, or conditions that could compromise the validity of analyses, the laboratory project coordinator will

immediately contact the Parsons ES team or project manager as part of the corrective action process.

- Samples will be logged into the laboratory management computer system, which includes a tracking system for extraction and analysis dates.
- The samples will be stored in a secured area at a temperature of approximately 4 degrees Centigrade (°C) (as applicable) until analyses commence.
- The samples will be distributed to the appropriate analysts, with names of individuals who receive samples recorded in internal laboratory records.
- The original COC form will accompany the laboratory report submitted to Parsons ES and will become a permanent part of the project records.

The laboratory will notify Parsons ES's team or project manager by telephone if the holding times specified by the required methods may be exceeded. The laboratory will provide alternatives for completing the specified analyses within the required holding time.

2.9.3 Sample Custody Records

Each sample will be logged into the laboratory system by assigning it a unique sample number. This laboratory number and the field sample identification number will be recorded on the laboratory report. Samples will be stored and analyzed as appropriate for the method specified on the sample containers.

The laboratory coordinator (or designee) will provide the Parsons ES team or project manager with a written report upon receipt of samples which includes, at a minimum, samples received, condition of samples upon receipt, field identification numbers, laboratory sample identification numbers, tests to be performed, and the projected date of completion of the specified analyses. In addition, the laboratory project coordinator (or designee) will provide Parsons ES's project QA officer with a written sample tracking report upon receipt of samples. This report will present, at a minimum, the following information for each sample received:

- Sample identification number,
- Date of sample collection,
- Location of sample,
- Date of laboratory receipt,
- Required analytical tests,
- Required date of extraction (if applicable),
- Required date of analysis, and
- Date analyzed or date of expected analysis.

If the data are directly acquired from instrumentation and processed, the analyst will verify that the following are correct:

- Project and sample numbers,
- Calibration constants and response factors,
- Output parameters such as units of measurement, and
- Numerical values used for detection limits if a value is reported as "below practical quantitation limit" (BQL), "below method detection limit" (BMDL), or "not detected" (ND)."

2.10 ANALYTICAL METHODS

Application of a specific analytical method depends on the analytes to be identified and the sample matrix. Methods for each of the parameters in the analytical program, as well as detection limits, are presented in the following subsections.

2.10.1 Identification of Methods

All of the analytical methods anticipated to be used as part of this program, and the source references for each method, are summarized in section 2 of the RAP. Not all of the analytes will be run for each sampling event. This list may be supplemented to support site-specific data needs. The laboratory shall use its standard operating procedures (SOPs) for each method identified.

2.10.2 Detection and Quantitation Limits

A method detection limit (MDL) is the lowest concentration that can be measured and reported with 99 percent confidence that the analyte concentration is greater than zero. MDLs are experimentally determined and verified for each analyte of the analytical methods in the sampling program. MDLs are based on the results of spiking reagent-grade water with a pure standard to achieve a concentration at the estimated detection limit for that analyte. The spiked sample is then carried through the appropriate extraction procedure and analyzed according to the method. The analytical results are then used to calculate the MDL for the method. All nondetected values will be reported at the MDL. The MDL will be the reporting level for this project. The confidence level for eliminating false negatives will be 99 percent for this project, which corresponds to two times the MDL, and will be called the reliable detection level (RDL) (RDL = 2 x MDL). The Required Quantitation Limit (RQL) is the concentration which is two times the RDL (RQL = 2 x RDL = 4 x MDL). This recognizes that the RDL estimates produced at different times by different operators for different representative matrices will not exceed the RQL. All MDLs will be less than the CRQL. The RQL may not be less than the CRQL. In these cases, the MDL will be the reporting level. The laboratory will provide the MDL studies to be used for this project for each method.

If an analyte is present at a concentration greater than the linear range of the analytical method, the sample must be diluted for accurate quantitation. The dilution factor (DF) raises the reporting limit above the RQL to a higher limit or sample quantitation limit (SQL). The SQL is equal to the RQL multiplied by the DF. The RQLs are equal to the SQL when the DF is equal to 1.

Detected concentrations lower than the RQL but greater than or equal to the RDL will be reported as estimated values only (flagged J). Detected concentrations less than the RDL will be reported as estimated values (flagged U). Nondetected concentrations are reported as undetected at the RQL. A complete description of laboratory flags follows in Section 2.10.3.

2.10.3 Laboratory Organic Data Reporting Flags

The following flags must be used by the laboratory when reporting results of organic analyses.

Value - If the result is a value greater than or equal to the practical quantitation limit (PQL), the value is reported.

U - Indicates the compound was analyzed for but not detected. The number is the project reporting level (e.g., the CRQL or MDL) for the sample.

J - Indicates an estimated value. This flag is used to estimate a concentration for tentatively identified compounds where a 1:1 response is assumed or when the mass spectral data indicate identification criteria, but the result is less than the specified detection limit. This flag will also be used to identify values falling between the MDL and the PQL.

UJ - A combination of the "U" and "J" qualifiers. The analyte analyzed for was not present above the level of the associated value. The associated numerical value may not accurately or precisely represent the concentration necessary to detect the analyte in the sample.

B - Used when the analyte is found in the blank, as well as in a sample. It indicates possible/probable blank contamination and warns the data user to take appropriate action.

2.10.4 Laboratory Inorganic Data Reporting Flags

The following flags (concentration and method) must be used by the laboratory when reporting results of inorganic analyses (such as nitrate, sulfate).

Concentration Flag:

B - The reported value was obtained from a reading that was less than the PQL, but greater than or equal to the MDL or IDL.

U - The analyte was analyzed for but not detected. The number is the project reporting level (e.g., the nondetect level) for the sample.

2.10.5 Sampling and Laboratory Calibration Methods

Instruments and equipment used to gather, generate, or measure the environmental data will be calibrated with sufficient frequency and in such a manner that accuracy and reproducibility of results are consistent with standards of the discipline, based on approved written SOPs. Records of calibration, repairs, or replacement will be filed and maintained by the designated personnel performing QC activities. These records will be filed at the laboratory and will be subject to QA audit.

For all instruments, the laboratory will maintain a factory-trained repair staff with in-house spare parts, or will maintain service contracts with vendors. Instruments and equipment used to gather, generate, or measure the environmental data will be calibrated with sufficient frequency and in such a manner that accuracy and reproducibility of results are consistent with standards of the discipline, based on approved written SOPs. Records of calibration, repairs, or replacement will be filed and maintained by the designated personnel performing QC activities. Calibration of instruments and equipment will be performed at time intervals as specified by the manufacturer, method, contract laboratory program (CLP) protocols, or more frequently, as conditions dictate. Calibrations will be performed at the start of each test run and verified throughout the analysis to the QC specifications of the appropriate analytical method. Such calibrations will also be reinitiated as a result of excess delay, or at such timely intervals as specified in the analytical method. In all cases, the laboratory's QAPP and SW-846 method-specified calibration procedures and frequencies take precedence over the following general guidelines.

2.11 DATA MANAGEMENT

Parsons ES has developed a data management plan to meet the data deliverable requirements of the risk-based remediation program. Laboratory data will be reported in a computerized format. All data entered into data files will correspond to the data contained in the original laboratory reports and other documents associated with sampling and laboratory activities. Parsons ES will supply the laboratory with a sample reporting diskette upon acceptance of a support contract. All data will be maintained in a Paradox™ data base or equivalent in a modified format taken from the Air Force Installation Restoration Program Information Management System (IRPIMS) Data Loading Handbook, Version 2.3, May 1994. The preferred format for data submittal is Excel™ .XLS. The laboratory will return the diskette with sample results within two weeks of acceptance of a contract. A satisfactory data reporting system will be completed within three weeks of acceptance of a contract. (Parsons ES will check the sample diskette for form and format and will provide assistance in correcting any problems noted on the reporting diskette.) The electronic reporting diskette is to be delivered along with two copies of the hard copy deliverables.

The laboratory will enter analytical test method, result, and QC data on data sheets which will be filed for permanent storage at the laboratory. A separate book will be maintained for each analytical procedure. The data entered will be sufficient to document all factors used to derive the final (reported) value for each sample. Calculations may include factors such as sample dilution ratios, corrections for blank readings, or conversion to dry-weight basis for solid samples. Instrument chart recordings and calculator printouts will be labeled and attached to their respective pages or cross-referenced and stored in the project file. Calculations for GC/MS analyses will be performed in the data system and kept in the system printout. These will be filed in chronological order.

Concentration units will be listed in reports, and any special conditions will be noted. The analysis report will include the unique sample number given to each sample and the dates of sample receipt and analysis.

2.12 DATA DELIVERABLES

Data deliverables required for the analytical results include both a hard copy and an electronic copy of field analytical results in a specified format and QA/QC results. Data reporting requirements are listed below.

2.12.1 Reporting Analytical Data

Reporting of analytical results for this project will include analytical results summaries for field samples, analytical results summaries for QC samples, and detailed data on analytical methods, procedures, and reporting levels. The following items will be reported to Parsons ES by the laboratory in the specified format. Note that many of these items are to be provided to the laboratory upon sample transmittal.

- Project identification,
- Site name,
- Abbreviated site name,
- Sample locations,
- Laboratory batch number,
- Sample collection date,
- Sample interval,
- Sample matrix,
- Sample QC code,
- Analytical method,
- Laboratory sample number,
- Extraction method,

- Extraction date,
- Parameter classification,
- Analysis date,
- Units of measure,
- Basis of measure,
- Chemical (parameter) name,
- Analytical result,
- Precision of analytical result,
- Detection limit,
- Precision of detection limit,
- Practical quantitation limit, and
- Practical quantitation limit precision.

Case narratives for each data report are to be provided. However, raw data system printouts will not be delivered as part of the report package. The laboratory will maintain these records so that they can be accessed and retrieved with nominal effort within the next 5 years. Format requirements will be established for both hard copy and electronic copy data reports.

2.12.2 Assessment of Data Usability

Data from QC samples will be assessed by Parsons ES using the procedures and criteria presented earlier in this section. This assessment will be a continuous process in which QA problems are identified immediately and the appropriate corrective action is implemented. Additionally, Parsons ES will assess the usability of analytical data. Any limitations on data use will be expressed quantitatively to the extent practicable and will be documented in any reporting of the data.

This data usability review will include a review of the analytical methods, quantitation limits, and other factors important in determining the precision, accuracy, completeness, and representativeness of the final data set (see Section 2.8 of this QAPP). The outcome of this data evaluation will be a data set appropriate to support quantitative fate and transport analyses and risk analysis. The data evaluation methods defined by EPA (1989b) in OSWER Directive 9285.7-01a *Risk Assessment Guidance for Superfund (RAGS), Volume 1: Human Health Evaluation Manual* (EPA/540/1-89/002) and OSWER Directive 9285.7-09a *Guidance for Data Usability in Risk Assessment* (EPA, 1992) will be used as appropriate.

Data will then be qualified according to intended use. The qualification of data will be based on the performance measures for the project specified during the design process and described in the QAPP. Any limitation of data use will be expressed quantitatively, if possible, and will be documented. Project reports containing analytical data or relying on analytical data will be reviewed to confirm that the data or results are presented correctly. These reports will be approved by management before release, publication, or distribution.

2.13 LABORATORY QUALITY CONTROL

QC samples will be analyzed routinely by the laboratory as part of the laboratory QC procedures. Laboratory QC results will constitute at least 10 percent of each data set generated, and will consist of analysis of blanks, replicates, standards, matrix spikes, and surrogate spikes. Surrogates will be added to all samples requiring GC/MS analyses. One method blank will be run for every 20 samples analyzed. These laboratory QC sample analyses will be run independently of the field QC samples. Results of these analyses will be reported with the sample data and kept in the project QC data file.

2.13.1 Method Blanks

To verify that the procedures and reagents used do not introduce contaminants that affect the analytical results, method blanks will be run for all analyses. The method blank will be prepared by addition of all reagents to a substance or matrix similar to the sample and undergo all of the procedures required for sample preparation. The resultant solution will be analyzed with the field samples prepared under identical conditions. Contaminants found in the blank sample shall not exceed three times the MDL. An analyte concentration in the blank of two times the MDL will be used as an advisory limit. Results greater than three times the MDL indicate a need for corrective action and will require reanalysis, within the holding time requirements, of the samples prepared with the blank for those parameters where the contaminant is an analyte of interest. Corrective actions shall be performed prior to proceeding with reanalysis. The reported data will not be corrected for method blank contamination.

2.13.2 Bottle Blanks

If bottles are cleaned in the laboratory, bottle blanks must be performed at 5 percent frequency for each cleaned lot of bottles, and verification of bottle cleanliness provided to Parsons ES for each project-specific analytical method. If precleaned bottles are purchased, certificates of cleanliness will be shipped with the bottles to the site.

2.13.3 Surrogate Spike Analyses

Surrogate spike analyses are used to determine the efficiency of analyte recovery in sample preparation and analysis. Calculated percentage recovery of the spike is used to measure the accuracy of the analytical method. A surrogate spike is prepared by adding to an environmental sample (before extraction) a known amount of a pure compound similar in type to the environmental sample to be assayed by GC/MS. Surrogate compounds will be added to all samples analyzed by GC and GC/MS methodology, including method blanks and duplicate samples. Compounds used as surrogates and their spike recoveries may be used as addressed in the laboratory QA plan. Surrogate spike recoveries should fall within the limits established by laboratory QC protocol. If a recovery is not within these limits, the corrective actions described in the method will be implemented.

2.13.4 Matrix Spike Analyses

To determine the effect of matrix interference on the results of GC and GC/MS analyses, aliquots of the same sample will be prepared in the laboratory, and each aliquot will be treated exactly the same throughout the analysis. Spikes are added at concentrations specified in the method. At a minimum, the laboratory must analyze the QC sample specified in the analytical method at the frequency indicated by the method. At least one matrix spike/matrix spike duplicate (MS/MSD) pair will be analyzed for every 20 project samples for each project analytical method. The relative percent difference (RPD) between the values of the spiked duplicates is taken as a measure of the analytical method precision.

Selected samples will be spiked to determine accuracy as a preliminary review (PR) of the analyte from the sample matrix. In exception to CLP-protocol, matrix spike and duplicate samples will be assigned in the field. The laboratory will notify Parsons ES's team or project manager in situations where the required MS/MSD samples have not been specified on the COC report to acquire identification of a MS/MSD sample. In an extreme situation where Parsons ES cannot be contacted and sample holding time will be adversely affected, the laboratory will select an appropriate sample for MS/MSD analysis. At all times, the required MS/MSD samples will be analyzed at the appropriate frequency for each matrix and analytical method. These matrix spikes will be prepared using reagent-grade salts, pure compounds, or certified stock solutions whenever possible. Concentrated solutions will be used to minimize differences in the sample matrix resulting from dilution. Samples will be split into identical duplicates, one of which will then be spiked with a known mass of the analyte. The final concentration after spiking should be within the same range as the samples being analyzed to avoid the need for dilution, attenuation of instrument outputs, or other required alterations in procedure which might affect the instrument response and determination of accuracy.

The results of the analyses will be reviewed by the laboratory supervisor. Deviations from established QC criteria will be noted, and reanalysis or another corrective action will be instituted as appropriate for the situation.

A laboratory control sample (LCS) will be analyzed during each initial instrument calibration and the recovery must be within the range of 80 to 120 percent. In the event of low spike recovery for MS/MSD samples analyzed by inductively coupled plasne (ICP), the results of an analytical spike (LCS/LCS duplicate [LCSD]) will be used to determine the need for reanalysis. The mean PR and standard deviation from a minimum of 20 analyses will be calculated. A warning limit of two standard deviations from the mean, and a control limit of three standard deviations will be used to determine if the test is providing accurate data. If the LCS/LCSD results are out of control, then corrective action is required and the batch must be reextracted and reanalyzed. When the analysis of the LCS/LCSD samples verify a matrix interference problem, all sample values for that batch will be qualified as estimated.

2.13.5 Second Column Confirmation

To ensure precision of analytical results at or near the MDL, a small subset of field ground water samples will be identified by Parsons ES for second column confirmation. Second column confirmation will be completed using GC/MS Method SW8240 (8260). No more than 10 percent of the ground water samples taken at each site will be marked for second column confirmation.

2.13.6 Quality Control and Audit

QC results will be calculated by the analyst and reviewed by the laboratory supervisor to determine the accuracy and precision of the analytical results. The laboratory supervisor or manager will review all final reports and associated QC data. Approval is shown by signature. Results will be recorded on the QC report forms for the appropriate tests and correlated to the analysis results. The QC results will also be used to prepare control charts for each test and type of matrix. The laboratory QC results and procedures will be available for review by Parsons ES for up to 2 years after completion of the work.

2.13.7 Control Limits

The QC checks, their frequency, acceptance criteria, and corrective actions for out-of-limit data are summarized in Appendix A for each analytical method listed as part of this program. The laboratory should supplement this criteria according to their SOPs and historical data. The degree of accuracy, or percent recovery, is dependent upon the sample matrix, specific analytical method, and the concentration of the analyte relative to its detection limit. The laboratory will identify control parameters for each analytical method, experimentally establish control limits and reevaluate them at regular intervals. The acceptance criteria for analyte recovery will be based on laboratory historical data. The laboratory will provide Parsons ES with this criteria within two weeks of acceptance of a contract. The laboratory may default to method-specified limits.

2.14 ACCEPTANCE CRITERIA FOR THE CONTROL LIMITS

The laboratory will perform in-house analytical data reduction and validation under the direction of the laboratory's QA officer. Laboratory control limits for matrix spikes, matrix spike duplicates, and surrogate spikes will be those presented in Appendix A. The laboratory's QA officer is responsible for assessing data quality and advising Parsons ES of any data which were rated "preliminary," "unacceptable," or otherwise which would caution the data user of possible unreliability. Data reduction, validation, and reporting will be conducted as follows:

- Raw data produced by the analyst are turned over to the respective area supervisor.

- The area supervisor reviews the data for attainment of QC criteria as outlined in EPA CLP protocols and/or established EPA methods and for overall reasonableness.
- Upon acceptance of the raw data by the area supervisor, a computerized report is generated and sent to the laboratory QA officer.
- The laboratory QA officer will complete a thorough audit of reports at a frequency of one in ten, and an audit of every report for consistency.
- The laboratory QA officer and area supervisor will decide whether any sample reanalysis is required.
- Upon acceptance of the preliminary reports by the laboratory QA officer, final reports will be generated and signed by the laboratory project manager. The components of the laboratory package will be presented in the same order in which the samples were analyzed.

Data reduction reporting procedures should be followed. The laboratory will prepare and retain full analytical and QC documentation similar to that required by the EPA CLP.

The laboratory will report the data in the same chronological order in which it is analyzed, along with QC data. For organic analyses, the data packages must include matrix spikes, matrix spike duplicates, surrogate spike recoveries, and GC/MS chromatograms and spectra.

A final QC requirement document, as well as a more specific deliverables list per method, will be provided prior to the beginning of the sampling event.

Parsons ES will conduct a systematic review of the data for compliance with the established QC criteria based on the spike, duplicate, and blank results provided by the laboratory. An evaluation of data accuracy, precision, comparability, and completeness will be performed and presented in the analytical data report.

Parsons ES will identify any out-of-control data points and data omissions, and will interact with the laboratory to correct data deficiencies. Decisions to repeat sample collection and analyses may be made by the Parsons ES project manager based on the extent of the deficiencies and their importance in the overall context of the project.

2.15 CORRECTIVE ACTION

The following procedures have been established to assure that conditions adverse to data quality, such as malfunctions, deficiencies, deviations, and errors, are promptly investigated, evaluated, and corrected.

All subcontractor personnel have the responsibility, as a part of normal work duties, to promptly identify, report, and solicit approved correction of conditions adverse to quality. Corrective actions may be initiated if any of the following conditions apply:

- Sample holding time limits are not met;

- Predetermined acceptance standards are not attained (objectives for precision, accuracy, and completeness);
- Reports or data compiled are determined to be inconsistent or faulty;
- Equipment or instrumentation is found to be faulty;
- Samples and test results are not readily traceable;
- QA requirements have been violated;
- Designated approvals have been circumvented;
- System and performance audit results warrant; or
- Management assessment results warrant.

2.15.1 Response to Out-of-Control Events

When a significant condition adverse to data quality is noted at the laboratory location, the cause of the condition will be determined, and corrective action will be taken (up to and including the laboratory replacement) to preclude repetition. Condition identification, cause, reference documents, and corrective action planned will be documented and reported to Parsons ES's QA/QC manager and involved management. Implementation of corrective action will be verified by follow-up action.

Appropriate corrective actions for laboratory conditions which would adversely affect data quality are listed below as follows:

- Observations corrected at the bench. If calibration of an instrument is not linear, the analyst will correct it before continuing to analyze samples. The laboratory will document this correction and note that the corrective action was to recalibrate and that no samples were affected, as none were analyzed prior to calibration.
- Corrective actions taken by laboratory supervisor. If a matrix spike recovery is out of control, and is discovered by the laboratory supervisor after the samples for the day have been analyzed, the supervisor will document the occurrence and the actions taken. Corrective action generally will consist of flagging the data as estimated.
- Corrective actions at the receiving level. If a sample container is broken, the analyst will note the breakage and document if more sample is available. If additional sample is not available, the laboratory will notify the Parsons ES task or project manager. Samples may be recollected if completeness criteria are jeopardized.
- Statistical out-of-control events. If a control chart is being monitored and the measured parameter exceeds the criteria, then the point at which the parameter exceeded the statistical limits will be documented. The data will be flagged as estimated, and the sample will be reanalyzed when QC is reestablished. The

conditions necessary to reestablish control and the criteria for ensuring that the system is operating properly will be documented.

2.15.2 Re-establishment of Control

Procedures for re-establishment of control after the occurrence of an out-of-control event include the specific actions described above. If samples are reanalyzed, the assessment procedures will be repeated, and the control limits will be reevaluated to ascertain if corrective actions have been successful.

2.15.3 Documentation

Out-of-control events and corrective actions will be documented in writing by the laboratory QA manager. Any nonconformance with the established QC procedures will be identified and corrected. A nonconformance report will summarize each nonconformance condition. Corrective actions will be implemented and documented. A stop-work order may be initiated by Parsons ES's project manager if corrective actions are insufficient.

2.16 QUALITY ASSURANCE REPORTS

2.16.1 Reporting Procedure

Periodic QA reports will be prepared by the laboratory QA manager for review by Parsons ES's project QA manager. Reports to be prepared include:

- Audit reports (periodic as needed), and
- Progress report (monthly).

2.16.2 Report Content

The specific content of reports will depend upon the type of report. In general, the reports will address:

- Changes in a QA project plan;
- Summary of QA/QC programs, training, and accomplishments;
- Results of technical systems and performance evaluation audits;
- Significant QA/QC problems, recommended solutions, and results of corrective actions;
- Data quality assessment relative to precision, accuracy, representativeness, completeness, comparability, MDL, and CRQL;
- Indication of whether the QA objectives were met; and
- Limitations on use of the measurement data.

2.17 FINAL SAMPLE DISPOSITION

Upon completion of all required analyses and acceptance of the data reporting by Parsons ES, the laboratory shall be responsible for proper disposal of any remaining samples, sample containers, shipping containers, and Styrofoam or plastic packing materials in accordance with sound environmental practice, based on the sample analytical results. However, the laboratory will give prior notification to and receive the approval of Parsons ES before disposing of any remaining samples. The laboratory shall maintain proper records of waste disposal methods and disposal company contacts on file for inspection.

2.18 STORAGE OF DATA

The laboratory will archive copies of all hard copy data, project reports, and electronic data files for a period of five years. The laboratory will then notify Parsons ES in writing requesting Parsons ES's written authorization to dispose of the archived data.

2.19 PREVENTIVE MAINTENANCE

2.19.1 Procedures

Equipment, instruments, tools, gauges, and other items requiring preventive maintenance will be serviced in accordance with the manufacturers' specified recommendations or written procedures developed by the operators.

2.19.2 Schedules

Manufacturers' procedures identify the schedule for servicing critical items in order to minimize the downtime of the measurement system. It will be the responsibility of the individual operator assigned to a specific instrument to adhere to the instrument maintenance schedule and to promptly arrange any necessary service. Servicing of the equipment, instruments, tools, gauges, and other items will be performed by qualified personnel.

The laboratory will establish logs to record maintenance and service procedures and schedules. All maintenance records will be documented and will be traceable to the specific equipment, instruments, tools, and gauges.

Records produced for laboratory instruments will be reviewed, maintained, and filed by the operators at the laboratories. The Parsons ES QA/QC manager may audit these records to verify complete adherence to these procedures.

2.19.3 Spare Parts

A list of critical spare parts will be requested from manufacturers and identified by the operator. These spare parts will be stored for availability and use in order to reduce downtime due to equipment failure and repair.

SECTION 3

DATA INTERPRETATION AND ANALYSIS

The risk-based approach to remediation is dependent on conservatively estimating levels of contamination that can remain onsite without posing an unacceptable risk to human health or the environment. The risk-based approach provides site-specific flexibility in determining which potential remedial alternatives afford the highest degree of long-term effectiveness appropriate for the current and future uses of a site. The EPA recognizes that the mere presence of a contaminant does not necessarily warrant remediation, and that the goal of remediation investigations is to determine what remedial actions are necessary to eliminate or minimize risks to human health and the environment (EPA, 1987b). Using site-specific data, a quantitative source-and-release analysis and an exposure pathway analysis will be completed as part of this project to determine which, if any, of the four contaminant phases (i.e., soil gas, contaminated vadose zone soils, free-phase product, and dissolved-phase contamination) may pose a risk to human health and the environment. Quantitative contaminant fate and transport models such as Bioplume II (Rifai et al., 1988) will be used to determine whether fuel contaminants could migrate to a potential receptor exposure point.

3.1 REMEDIAL GOALS

For each of the eight demonstration sites, site-specific data will be used to aid in the selection of a low-cost source removal technology which reduces the risk associated with petroleum hydrocarbon contamination. Remediation goals will be developed to address site-specific conditions. These remediation goals will aid in determining the most cost-effective remedial technology for the site by identifying which media and which contaminants need to be addressed to protect human health and the environment. All developed remediation goals will be based on widely accepted risk assessment guidance (e.g., EPA Risk Assessment Guidance for Superfund, Volume 1: Human Health Evaluation, Part B - Development of Risk-Based Preliminary Remediation Goals). All calculated remedial goals will be developed by Parsons ES personnel familiar with risk assessment procedures. Final remediation goals will be critically reviewed by an Parsons ES senior or supervisor risk assessor, the technical director, and the project manager.

3.2 BIOPLUME II MODEL

After the site has been adequately characterized using both historical data and data collected under this project, fate and transport analyses will be performed to determine the potential for contaminant migration and whether any exposure pathway is complete. The Bioplume II computer model (Rifai et al., 1988) will be used to predict plume migration and contaminant attenuation by natural biodegradation.

The Bioplume II model will be used to assess the influence of key electron acceptors on the fate and transport of contaminants. The Bioplume II model is based upon the U.S. Geological Survey (USGS) two-dimensional (2-D) solute transport model MOC, which has been modified to include a biodegradation component activated by a superimposed plume of dissolved oxygen. However, as part of this demonstration project, the biodegradation of fuel contamination will be simulated based on the actual assimilative capacity of the ground water. Work completed as part of the Natural Attenuation (Intrinsic Remediation) demonstration program, also sponsored by AFCEE, suggests that many compounds can act as electron receptors at a fuel site. Incorporating additional electron acceptors into the Bioplume II model should provide a better estimate of the effectiveness of natural attenuation processes at minimizing contaminant migration and reducing contaminant mass and toxicity. Use of possible electron acceptors should also provide a better estimate of response time. Use of oxygen as the only electron acceptor can seriously underestimate the effects of natural degradation processes.

Bioplume II solves the USGS 2-D solute equation twice, once for hydrocarbon concentrations in the ground water and once for a dissolved oxygen plume. The two plumes are then combined using superposition at every particle move to simulate biological reactions between fuel products and oxygen. Using even the most realistic, conservative data, Bioplume II generally predicts very limited migration of BTEX plumes due to natural attenuation processes. Bioplume II has been used to simulate the effectiveness of intrinsic remediation at several sites (e.g., Wilson et al., 1986; Chiang et al., 1989; Rifai et al., 1988; Malone et al., 1993; Wiedemeier et al., 1993).

The risk-based approach to remediation is aimed at providing scientific evidence of the positive effects of intrinsic remediation and other innovative source removal technologies. The type and magnitude of these effects will be factored into the development of a final remedial alternative for the site. It is likely that intrinsic remediation alone will be insufficient at many fuel hydrocarbon-contaminated sites to reduce or eliminate contaminant migration and receptor risks. Other innovative source removal technologies, such as bioventing, will be included in the fate and transport calculations, risk analysis, and remedial design as necessary to ensure that the final remedial alternative will protect current and future receptors from adverse exposures to any site-related contamination (e.g., soil gas, soil, and ground water).

The Bioplume II model has been validated as a commercial package by Parsons ES personnel. A series of tests was performed to verify that the model is capable of yielding valid results. Any assumptions made during the actual modeling will be documented and discussed in the technical report. The model software will be run by Parsons ES personnel with knowledge of both the theory of contaminant fate and transport and the computer software to ensure that defensible conclusions can be drawn from the results. Any other models used to estimate exposure point concentrations as part of designing a remedial approach for a site will be validated as a commercial package. Any assumptions and uncertainties associated with model development and results will be clearly identified.

3.3 RISK DETERMINATION

The potential risks to human and ecological receptors will be determined by comparing calculated exposure concentrations derived from field data and quantitative fate and transport analyses to the remediation goals identified to be protective of human health and the environment given site-specific conditions. Comparison of these values will determine the type and magnitude of remediation that will be necessary to minimize risks to the maximum extent practicable.

3.4 DEVELOPMENT OF AN APPROPRIATE REMEDIAL APPROACH

Using both the risk calculation and Bioplume II modeling results, remedial technologies will be identified and evaluated based on

- long-term effectiveness and ability to reduce contaminant toxicity, mobility, or volume;
- technical and administrative implementability; and
- cost.

The risk-based approach to remediation is intended to quickly define a remedial alternative for each specific site that will reduce or eliminate significant risks to human health and/or the environment. An RAP will be prepared for the site to document the approach used to identify an appropriate remedial action. The RAP will provide sufficient technical data on the recommended remedial alternative to show that it eliminates or abates present and future threats to human health and the environment to the maximum extent possible, and that appropriate control measures such as long-term monitoring are designed to supplement intrinsic remediation or any engineering controls.

3.5 EVALUATION OF SOURCE REMOVAL/RISK REDUCTION OPTIONS

To provide adequate data and analyses in support of the selection, design, and implementation of an appropriate remedial alternative, it will be necessary to critically evaluate single or combined remedial technologies in terms of long-term effectiveness, implementability, and cost. Field data, quantitative fate and transport modeling designed to explore the potential effectiveness of natural attenuation processes, and several other institutional and engineering technologies will be evaluated for their risk reduction potential. Combinations of institutional controls and cost-effective site remediation methods will be evaluated. Based on guidance from AFCEE, a minimum of three options will be evaluated for a site. Each option will be evaluated against three primary criteria: protectiveness of human health and the environment, implementability, and cost.

Effectiveness - Each remedial alternative will be analyzed to determine how effectively it will protect both current and future receptors from potential risks associated with contamination. This analysis will be based on determining whether the remedial alternative can achieve and maintain final remediation goals. Effectiveness will also include permanence and ability to reduce contaminant mass, volume, and toxicity.

Implementability - The technical implementation of each remedial option will be evaluated. The expected technical effectiveness of each remedial alternative will be described. Potential shortcomings and difficulties in construction, operations, and monitoring will be presented and weighed against perceived benefits. The administrative implementation (regulatory and community acceptance) of each remedial approach also will be discussed. This is an important element of the RAP, particularly when intrinsic remediation is determined to be the most cost-effective method of risk reduction.

Cost - The estimated cost of each remedial option will be presented. Both capital and operating costs will be estimated, along with a present worth cost estimate for the predicted operating life of each option. Cost assumptions will be clearly stated and the cost sensitivity of assumptions discussed.

It is important to note, however, that the most effective remedial technology or remedial alternative may not be the most cost-effective option for the site. A cost-effective remedial alternative is one that achieves the best balance between long-term effectiveness and cost of all the remedial alternatives which meet the cleanup objectives for the site. The test of cost-effectiveness may be more extensive for a range of remedial alternatives which vary only in degree of long-term effectiveness, but which will all achieve the site cleanup goals. The remedial alternative which achieves the site cleanup goals at the lowest cost will be identified. The total cost for the other remedial alternatives will also be estimated, and all remedial alternatives will be ranked according to their degree of long-term effectiveness. The remedial alternative that provides the best balance between long-term effectiveness and cost would be the most cost-effective.

3.6 SELECTION OF A RECOMMENDED APPROACH

Based on an evaluation of the protectiveness, implementability, and cost of each option, Parsons ES will recommend the option which provides the greatest protection for the lowest cost.

If this comparison indicates that natural attenuation of site contamination is occurring and is sufficient to reduce the potential risks to human health and the environment to acceptable levels, Parsons ES will recommend implementation of natural attenuation with long-term monitoring as the preferred remedial alternative. Otherwise, Parsons ES will use an iterative process to identify and design an appropriate remedial approach that couples at least two low-cost remedial technologies. If additional remediation of the source area is recommended, a conceptual design of the remediation system will be prepared and included in the RAP for Air Force and regulatory review. If bioventing is selected for source removal, any existing designs will be updated to include any areas of soil contamination discovered during the site investigation activities conducted as part of this project. If intrinsic remediation is an integral part of the recommended option, a long-term monitoring plan will be developed to ensure that both soil and ground water contamination are decreasing according to the remediation strategy.

3.7 LONG-TERM MONITORING PLAN

A site-specific, long-term monitoring plan will be included as part of the RAP. This plan will specify the location of confirmation and point-of-compliance wells and sampling frequencies to demonstrate long-term effectiveness and permanence of the selected remedial alternative. Long-term monitoring as part of this demonstration project will likely involve the installation and sampling of confirmation and point-of-compliance wells. Confirmation wells will be located immediately downgradient of the existing plume and will provide for early confirmation of model and engineering predictions. The point-of-compliance wells will be located further downgradient to verify that site-related contamination does not pose an unacceptable risk to potential receptors over time. All point-of-compliance wells will be located and established in concert with regulatory agencies and cognizant base officials. Any requirements for institutional controls or long-term monitoring required to protect human health and the environment will be clearly described in the RAP. Requirements for long-term monitoring will depend upon the permanence or degree of long-term effectiveness afforded by the recommended remedial alternative.

Following the implementation of any required source removal technologies at the site, Parsons ES will operate the source removal system for a total of 600 days. At the end of the 600 days of treatment, Parsons ES will return to the site and resample soils in the source area to determine the degree of contaminant removal and evaluate the potential impact of source removal on the long-term fate and transport of contamination. A letter report will be prepared outlining the interim source removal results, the potential impact on the ground water plume, and the need for continued source removal if required.

3.8 REGULATORY COORDINATION STRATEGY

Following AFCEE and base review of the draft RAP, comments will be incorporated into a final draft for regulatory review and approval. When the final draft is completed, AFCEE and Parsons ES will provide a technical presentation to base officials and regulatory agencies to familiarize them with the key findings and recommendations of the RAP. Copies of the RAP will be provided to regulators at the meeting and a 30-day review will be requested.

SECTION 4

DESIGN, CONSTRUCTION, AND OPERATION OF ENVIRONMENTAL TECHNOLOGY

4.1 PLANNING

Project-specific planning for environmental technology involves key users and customers of the systems, as well as those responsible for activities affecting quality. Results of these planning activities are subject to reviews for conformance to technical and quality requirements.

System planning is coordinated among organizations participating in the activities and includes the following elements at a minimum:

- Program/task scope and objectives, and a list of the primary activities involved;
- Identification of the individuals needed to participate in the project and their roles in planning, design, construction, operation, and maintenance activities;
- Specific system components to be designed, constructed, and operated;
- Technical, performance, regulatory, and quality standards, criteria, or objectives;
- Personnel, equipment, and other resources required;
- Delivery, handling, storage, identification, inspection, testing, and installation requirements;
- Program technical reviews, peer reviews, and system assessments;
- Acceptance criteria for completed systems; and
- Project and QA records required.

Documentation of project and activity planning includes the appropriate use of work plans, QAPPs, design criteria, schedules, and conceptual design drawings.

4.2 DESIGN OF SYSTEMS

The Parsons ES design control system is documented and implemented using procedures generated in conformance with this QA program, as well as Parsons ES engineering policies, procedures, and standards. The system also provides the controls necessary to maintain conformity of Parsons ES design projects. Technology designs will be standardized and then modified for individual site applications.

The design control program includes control of design inputs (design basis, design criteria, regulatory requirements, codes and standards, fire protection, reliability data, environmental data, and computer programs), design process controls, outputs (specifications, drawings, procedures, analyses), design changes, configuration control systems, records, and organizational interfaces. Design control requirements for procured design and engineering services are incorporated into procurement specifications. Changes to the design documents will receive the same review and approval as the original document. The design input document is translated into design output documents in drawings, procedures, and specifications.

Nonconforming items, field changes, and modifications must be justified, documented, and evaluated using the same design basis (input documents) as were used in the original design. Such changes are reviewed and approved by the same design organization that reviewed and approved the original, or an approved alternate organization. All design changes will result in revisions to applicable design documents.

Design interfaces are identified and controlled, and design efforts are coordinated among participating organizations. Interface controls address responsibilities, reviews, design basis, deliverables, and associated approvals and requirements by which configuration management is maintained.

The design control program provides controls to ensure that records and documents are maintained to provide evidence of the acceptability of the design and continued configuration. Design records are maintained to support the basis and activities of the design process. These records shall include the design input basis documents, calculations, approved drawings and their revisions, computer programs, analyses, and prototype testing data. Documents supporting the design configuration and the final performance per the design basis are verified and retained.

Design analysis is validated to ensure that correct input data and assumptions are incorporated into the computer software program, and are verified to ensure that correct solutions to physical problems are produced within predetermined limits. The documented computer software program requires that the process and changes are documented and approved by qualified technical personnel.

The design verification review is conducted by qualified individuals or groups other than those who prepared the original design. The design reviewer may be from the same organization as the designer, provided that the reviewer did not have responsibility for the original design effort. The reviewer may be a supervisor if other design personnel are not available and if the supervisor did not do the original calculation. Design verification does not need to be duplicated for multi-use items intended for the same application. The extent of the design verification is based on the complexity of the item and its importance to safety and reliability.

Design documents are verified in one of three ways: by conducting a formal design review, by producing alternate calculations, or by performing qualification testing. A single design verification may be applied for multiple items when a design is based on a single application and performance requirement.

4.2.1 Readiness Review

The Parsons ES QA Program provides for a system review to assure the readiness of projects, activities, or systems where completion (or completion of its phases) has been achieved. Verification of system readiness is required before final client inspection.

4.3 CONSTRUCTION/FABRICATION OF SYSTEMS AND COMPONENTS

The Parsons ES QA Program requires that the construction (fabrication/manufacture/erection) of engineered environmental systems be performed under appropriately controlled conditions according to the drawings, specifications, and requirements of the approved design. Only qualified and accepted services or items are used in those places indicated in the design. Identification of acceptability is maintained on such items themselves, in documentation traceable to the items, or in a manner ensuring identification.

All components and systems are installed according to current, approved designs. All in-process and final inspections are planned and specified. Acceptance of engineered environmental systems is contingent upon meeting or exceeding expected performance criteria.

4.3.1 Inspections and Tests

Inspections or tests are performed at appropriate points during the construction/fabrication process to verify conformity to design specifications. Such inspections or tests are planned and specified and clearly reflect the acceptance criteria applied. Equipment or material which does not meet specifications will not be installed and will be returned to the equipment manager for turn-in and crediting.

4.3.2 Control of Items

Handling, storing, cleaning, packaging, shipping, and preserving equipment, components, and parts are controlled during construction/fabrication to prevent damage, loss, and deterioration. Items in storage are checked periodically to prevent and detect possible deterioration.

4.4 OPERATION OF SYSTEMS

Engineered environmental systems are operated according to approved design documentation and operation and maintenance manuals. Such operating guides include, but are not limited to:

- Operating procedures and maintenance requirements for specific components and system configurations; and
- Manufacturer information, specifications, and schematics of key system components.

4.4.1 Status Indicators

Status indicators are provided to indicate the operating status of systems and components. The indicators prevent inadvertent operation, or removal from operation, of any system or component when such actions would adversely affect performance of the systems, constitute an operational safety or environmental hazard, or violate statutory/regulatory compliance requirements.

4.4.2 Inspection and Test Control

Inspections or tests are performed periodically during operation to verify conformity to operating specifications or parameters. Such inspections or tests clearly indicate the acceptance criteria applied.

Periodic preventive and corrective maintenance of engineered systems is performed according to operating guidance and/or design specifications to ensure satisfactory system performance. The availability of critical spare parts is established and maintained according to operating experience, manufacturer's guidance, and/or design specifications.

4.5 INSPECTION AND ACCEPTANCE

4.5.1 Inspection

The Parsons ES QA program provides for the development of inspection plans and procedures and for the conduct of inspections to ensure that the design requirement are met. Types of inspections are: receiving inspections, in-process inspections, source inspections, examination, and required code in-service inspections. Inspections are conducted on activities or items affecting quality to verify conformance with codes, standards, regulatory requirements, procedures, and procurement documents or specific client requirements.

4.5.2 Acceptance Testing

The Parsons ES QA program requires the Responsible Manager to identify items to be tested and to develop testing procedures. The testing procedures provide direction and inspection criteria by which testing can demonstrate that items and services are satisfactory in service and meet design acceptance requirements. The scope of acceptance testing includes, as appropriate, receiving inspection testing, post-maintenance testing, testing of installed equipment, and in-service systems testing.